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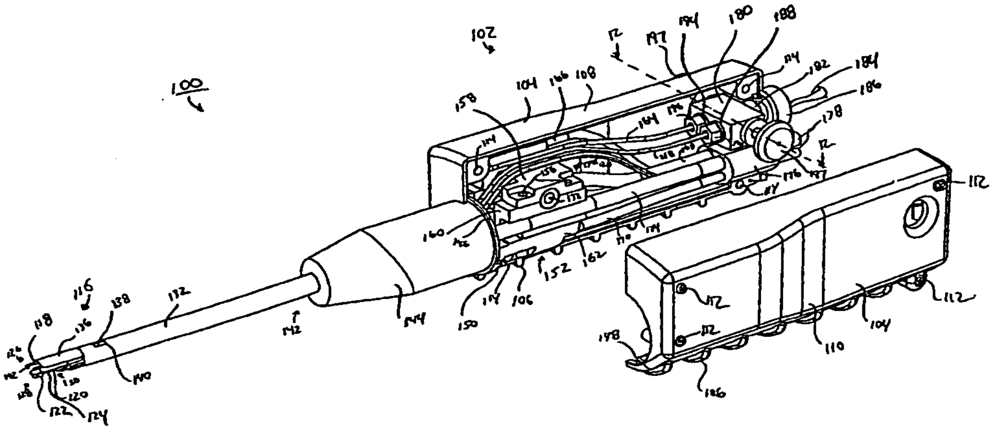
(54) Title: LIQUID JET-POWERED SURGICAL INSTRUMENTS



(57) **Abstract:** The present invention provides a series of devices useful for surgical procedures utilizing rotatable components for grinding, cutting, ablating, polishing, drilling, screwing, etc., tissues of the body of a patient. The invention includes, in one aspect, a series of devices comprising surgical instruments including rotatable shafts, and surgical components drivable by the shafts that can be utilized for contact with tissue in a surgical operating field. Some preferred surgical instruments provided by the invention utilize a liquid jet-driven rotor mechanism for driving rotation of the rotatable shaft. Some preferred instruments provided by the invention include both a liquid jet-driven rotor mechanism and a nozzle at the distal end of the instrument for forming a liquid cutting jet for cutting or ablating tissue of a patient. Such instruments can include a liquid flow directing valve therein that includes a pressure-tight sealing component comprising a sealing element that is constructed and arranged to be slidably moveable within a cylinder of the valve. The invention provides methods for utilizing the inventive surgical instruments in surgical procedures involving both cutting or ablating tissue of a patient with a liquid cutting jet and grinding, cutting, or ablating tissue with a rotating surface of a surgical instrument.

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LIQUID JET-POWERED SURGICAL INSTRUMENTS

FIELD OF THE INVENTION

The invention relates to surgical instruments, more specifically to surgical instruments providing rotating shafts for performing surgical functions, and to methods for using the instruments in surgical procedures.

BACKGROUND OF THE INVENTION

Traditionally, many surgical procedures have been performed on patients using open surgical methods that utilize relatively large incisions to expose a surgical field. Many traditional methods have also typically utilized surgical tools such as scalpels, scrapers, blunt dissectors, lasers, electrosurgical devices, etc., which can have poor tissue differentiating capability and which can sometimes cause inadvertent damage to tissue surrounding a surgical treatment site unless carefully utilized. Open surgery with such prior art surgical instruments often involves extensive trauma to the patient, with associated problems of long recovery periods and potential complications.

There has been a trend in recent years to perform many surgical procedures using less invasive techniques by accessing surgical sites via small holes through the skin or through body orifices. These techniques are known as “minimally invasive surgery.” Minimally invasive surgical techniques commonly employed include endoscopic, laparoscopic, and arthroscopic surgical procedures. Minimally invasive surgical procedures are commonly preferred to open surgical procedures for many applications because the minimally invasive procedures induce less trauma to the patient during surgery and involve, in many cases, fewer potential complications and reduced recovery time.

A variety of surgical instruments have been developed and utilized both for minimally invasive surgical procedures and for more traditional open surgical procedures. Frequently used instruments include blade and scalpel-type instruments, motorized rotary cutting and/or grinding instruments, laser instruments, liquid jet cutting instruments, and electrosurgical instruments. Typically, prior art instruments suffer from a variety of disadvantages. For example, typical prior art surgical instruments, especially those utilized for minimally invasive surgical procedures, have distal ends including a single component for performing a particular surgical function. Surgical instruments having distal ends including, for example, a rotating cutting or grinding head, a tissue-ablating laser, a liquid cutting jet, or an electrosurgical cutting jet are known in the art. Many of these prior art instruments suffer that surgical instruments be coupled to a source of highly pressurized gas during operation of the instruments, which can be inconvenient, expensive, or undesirable.

U.S. Patent No. 5,803,733 to Trott et al. describes a pneumatically powered surgical handpiece in which the pressurized fluid inlet is axially directed relative to the handpiece body. The handpiece includes a reaction-type turbine that is rotated by fluid flowing within a closed conduit. The handpiece utilizes a cantilevered turbine rotor, wherein the output shaft of the handpiece and the turbine rotor rotate about axes which are co-linear.

Surgical instruments utilizing liquid-driven turbine rotors are also known. U.S. Patent No. 4,631,052 to Kensey describes an elongated, flexible recanalization catheter that includes a working head which is adapted to be rotated by a turbine drive in operation. The turbine drive utilizes a liquid-driven turbine rotor comprising a reaction turbine whose rotational motion is imparted by pressure driven liquid flowing in a closed conduit. The turbine rotor and the rotating working head of the device are directly coupled together so that they rotate at essentially the same speed during operation. In addition, the rotor assembly is disposed at the distal end of the catheter and is essentially completely submerged in liquid during operation.

U.S. Patent No. 4,690,140 to Mecca describes a catheter for use in the removal of deposits lining the interior wall of a blood vessel that includes a rotating cutting device at its distal end. Rotational motion of the rotating cutting device is imparted by flow of a pressure-driven liquid. The cutting surfaces of the rotating cutting device and the turbine rotor comprise a single component rotating at essentially the same speed and about the same rotational axis. As with the '052 patent described above, the rotating cutting element of the '140 patent is disposed at the distal end of the catheter such that the turbine rotor causing rotation of the device is essentially completely submerged in liquid during operation.

Surgical instruments providing electrosurgical cutting or cauterizing electrodes in combination with rotating surgical components or liquid perfusion and/or aspiration capabilities are also known.

U.S. Patent No. 5,527,331 to Kresch describes a tissue resection device for use in an organ inflated with a non-conductive fluid. The distal end of the device can include a perfusion lumen, a rotatable drive tube, and a drive tube aspiration lumen. A cutting tip can be mounted on the distal end of the drive tube. In some configurations, the cutting tip is further configured to act as an electrosurgical resection electrode.

U.S. Patent No. 5,941,876 to Nardella et al. describes an electrosurgical apparatus that includes a rotary, tissue affecting device, such as a rotating blade component, a rotating drill,

SUMMARY OF THE INVENTION

The present invention provides a series of devices useful for surgical procedures utilizing rotatable components for grinding, cutting, ablating, polishing, drilling, screwing, etc., tissues of the body of a patient. The invention includes, in one aspect, a series of devices comprising surgical instruments including rotatable shafts, and surgical components drivable by the shafts that are constructed and arranged for contact with tissue in a surgical operating field. In another aspect, the invention provides a pressure-tight sealing component comprising an element constructed and arranged to be slidably moveable within a cylinder and, in yet another aspect, the invention provides a method for utilizing the inventive surgical instruments.

In one aspect, a series of devices comprising surgical instruments are described. One device comprises a surgical instrument having a distal end adapted to perform a surgical procedure on a patient and a proximal end adapted to be controllable by an operator. The instrument includes a rotatable shaft. The instrument further includes a surgical component that is drivable by the shaft and constructed and arranged for contact with a tissue in a surgical operating field. The instrument further includes a liquid jet-driven rotatable rotor. The rotor is drivingly coupled to the rotatable shaft, when the instrument is in operation, such that the rotation of the liquid jet-driven rotatable rotor causes a corresponding rotation of the rotatable shaft. Furthermore, the liquid jet-driven rotatable rotor is maintained in a surrounding gaseous environment while being rotatably driven by at least one liquid jet during operation, so that essentially no part of the rotor is submerged in liquid.

Another device comprises a surgical instrument having a distal end adapted to perform a surgical procedure on a patient and a proximal end adapted to be controllable by an operator. The instrument includes a pressure lumen having sufficient burst strength to conduct a high pressure liquid towards the distal end of the instrument. The pressure lumen includes at least one nozzle providing a jet opening. The nozzle is shaped to form a liquid cutting jet as a liquid at high pressure flows therethrough. The instrument further includes a rotatable shaft and a surgical component that is drivable by the shaft and is constructed and arranged for contact with tissue in a surgical operating field.

Yet another device comprises a surgical instrument having a distal end adapted to perform a surgical procedure on a patient and a proximal end adapted to be controllable by an operator. The instrument includes a rotatable shaft and a surgical component that is drivable by the shaft and constructed and arranged for contact with tissue in a surgical operating field.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic, perspective illustration of a surgical liquid jet instrument providing a liquid cutting jet and a rotating burr at its distal end, with the body of the instrument disassembled to show the internal components thereof;

FIG. 2A is a schematic, exploded, perspective illustration of a portion of the surgical instrument as in FIG. 1 showing the sheath and collar and components contained therein;

FIG. 2B is a schematic, cross-sectional illustration of the distal end of the surgical instrument as in FIG. 2A showing the distal end of the rotatable shaft and the support element therefor;

FIG. 2C is a schematic, cross-sectional illustration of the rotatable shaft and support element of the instrument as in FIG. 2B;

FIG. 3 is a schematic, perspective illustration of the surgical instrument as in FIG. 1, excluding the body of the instrument, and as viewed from the proximal end of the instrument;

FIG. 4 is a schematic, partially-cutaway, perspective illustration of the surgical instrument as in FIG. 1, wherein the sheath component has been rendered transparent;

FIG. 5A is a schematic, perspective illustration of a portion of a surgical instrument showing an alternative embodiment for providing a distal end including a liquid cutting jet and a rotatable grinding burr;

FIG. 5B is a schematic, perspective illustration of a portion of a surgical instrument showing another alternative embodiment for providing a distal end of a surgical instrument providing both a liquid cutting jet and a rotatable grinding burr;

FIG. 6A is a partially-cutaway, schematic illustration of a portion of the distal end of a surgical liquid jet instrument for creating a liquid cutting jet in a surrounding liquid environment;

FIG. 6B is partially-cutaway, schematic illustration of a portion of the distal end of a surgical liquid jet instrument for creating a liquid cutting jet in a liquid environment, where the evacuation lumen includes a constriction;

FIG. 6C is a schematic illustration of a portion of the distal end of a surgical liquid jet instrument, illustrating various geometric relationships;

FIG. 7A is a schematic, perspective illustration of a portion of a rotatable shaft including a grinding burr at its distal end, where the rotatable shaft includes a helically grooved channel disposed on at least a portion of the outer surface of the shaft;

FIG. 7B is a schematic, perspective illustration of a portion of a rotatable shaft including a grinding burr, where the rotatable shaft includes an impeller thereon;

FIG. 7C is a schematic, perspective illustration of a portion of a rotatable shaft with a grinding burr thereon and including a scoop shaped aperture in fluid communication with a channel defined by a hollow center of the shaft;

FIG. 8A is a schematic, exploded, perspective illustration of the rotatable shaft drive mechanism of the instrument as in FIG 1;

FIG. 8B is a schematic, perspective illustration of a rotor assembly and rotatable shaft drive assembly of the rotatable shaft drive mechanism as in FIG. 8A;

FIG. 8C is a partially-cutaway, schematic illustration of a portion of the rotatable shaft drive mechanism as in FIG. 8A showing the arrangement of the liquid jet nozzle, rotatable rotor, and liquid jet evacuation lumen;

FIG. 8D is a schematic illustration of the liquid jet evacuation lumen and rotor assembly as in FIG. 8C, as viewed from above;

FIG. 8E is a schematic, perspective illustration of a portion of the evacuation lumen as in FIG. 8D;

FIG. 9A is a schematic illustration of a saw-tooth rotor;

FIG. 9B is a schematic illustration of a portion of the saw-tooth rotor as in FIG. 9A, as viewed from above;

FIG. 10A is a schematic, perspective illustration of a curved-vein rotor;

FIG. 10B is a schematic illustration of several curved veins of the curved-veined rotor as in FIG. 10A;

FIG. 11A is a schematic illustration of one embodiment of a configuration for providing evacuation for a surgical instrument;

FIG. 11B is a schematic illustration of another embodiment for providing evacuation for a surgical instrument;

FIG. 12 is a schematic, cross-sectional illustration of the liquid flow directing valve of the instrument as in FIG. 1;

FIG. 13 is a schematic, cross-sectional illustration of the pressure-tight sealing component and spacer component of the liquid flow directing valve as in FIG. 12;

FIG. 14A is a schematic illustration of a rotatably deployable surgical liquid jet instrument including integrated electrocautery electrodes;

Certain preferred surgical instruments, provided according to the invention, are configured as surgical handpieces having a proximal end with a grasping region, or body, shaped and configured to be comfortably held in the hand of an operator. The instruments also have a distal end that includes at least one component constructed and arranged for contact with tissue. As discussed in more detail below, in certain embodiments, the above-mentioned component can comprise the distal end of a rotatable shaft, which may include, for example, a grinding burr, a cutting blade, a drill, a screwdriver, or other component.

In certain preferred embodiments, the instruments have a distal end that includes at least one nozzle for forming a liquid cutting jet. The distal end of the various inventive surgical instruments can be utilized, in certain preferred embodiments, to perform a surgical procedure on a patient. Although the surgical instruments described herein are shown as having a handpiece configuration, it should be understood that the invention is not strictly limited to surgical handpieces, and that the invention may also be practiced utilizing instruments including at least one liquid jet forming component but having a variety of alternative configurations and purposes. For example, instead of being configured as a surgical handpiece, the inventive surgical instruments could be configured for manipulation by machine control, such as a X/Y/Z positioning machine. Also, for embodiments involving instruments providing a liquid cutting jet at the distal end of the instrument, the liquid jet instrument can be used in a wide variety of surgical applications and utilize the high pressure liquid cutting jet to cut, drill, bore, perforate, strip, delaminate, liquefy, ablate, shape, form, etc. various tissues, organs, etc. of the body of a patient.

The liquid jet surgical instruments provided by the invention preferably include at least one pressure lumen that has a distal end terminating in at least one nozzle that provides a liquid jet opening, and that has a proximal end that is connectable so as to be in fluid communication with a source of liquid under high pressure, supplied, for example, by a high pressure pump or high pressure liquid dispenser. The liquid jet nozzle is shaped to form a liquid jet as a liquid under high pressure flows through the nozzle as described in greater detail below. The liquid jet, in certain embodiments, is used to create a driving force for rotating a rotatable shaft of the instrument that can extend, in preferred embodiments, from the body of the surgical instrument towards the distal end of the instrument. In some embodiments, the instrument includes a pressure lumen that conducts a high pressure liquid toward the distal end of the instrument and that includes at least one nozzle that creates a liquid cutting jet as a high pressure liquid flows therethrough. The liquid cutting jet, for rotatable shaft for performing surgical procedures, a liquid flow directing valve may be included within the body of the surgical instrument. The valve can function to direct a high pressure liquid to the pressure lumen within the surgical instrument that is in fluid communication with the liquid cutting jet forming nozzle at the distal end of the instrument, to the pressure lumen that is in fluid communication with the nozzle forming a liquid jet configured to drive rotation of the rotatable shaft, or to both simultaneously.

Preferred embodiments of the inventive surgical instruments that are configured to provide a liquid cutting jet at their distal end also include a liquid jet target or dissipater that is locatable opposite the jet opening orifice in the nozzle from which the liquid cutting jet is emitted (hereinafter referred to the "liquid jet opening" or "jet opening") at a predetermined distance from the liquid jet opening in order to receive and/or dissipate energy of a liquid cutting jet, when the instrument is in operation. Embodiments including a target or dissipater are preferred because the target/dissipater prevents the liquid cutting jet from being misdirected during use and potentially causing damage to unintended tissue sites in the surgical operating field. The target/dissipater enables the instrument to provide a predetermined liquid cutting jet length defined by the predetermined distance between the liquid jet opening in the nozzle and the surface of the target/dissipater upon which the cutting jet impinges. With such embodiments, the liquid cutting jet can be utilized for performing surgical cutting or ablating of tissue with a reduced danger of causing unintended collateral damage to tissue lying beyond the target/dissipater in the surgical operating field.

In some embodiments, the target/dissipater can be simply a solid surface capable of dissipating the energy of a liquid cutting jet by transforming the liquid jet into a harmless spray. In more preferred embodiments, however, the target is defined by a jet-receiving opening included in an evacuation lumen that forms part of the surgical instrument. In the preferred embodiments of instruments including an evacuation lumen having a jet-receiving opening, in addition to providing a defined liquid jet length (defined by the predetermined distance between the liquid jet opening and the jet-receiving opening) and preventing unintended damage as discussed above, the evacuation lumen can also be utilized for removing liquid, ablated tissue, and debris from the surgical field. In some embodiments of surgical jet instruments having an evacuation lumen for receiving a liquid cutting jet according to the invention, an external source of suction, for example a vacuum pump or aspirator, can be provided in fluid communication with a proximal end of the evacuation lumen in order to provide the suction driving force required for evacuating material from the instrument is in operation. Such devices can be configured as surgical handpieces for use, for example, in endoscopic, arthroscopic, or other surgical procedures.

As is described herein, and in much greater detail in commonly owned co-pending U.S. Patent Application No. 09/313,679, entitled FLUID JET SURGICAL INSTRUMENTS, incorporated herein by reference, the inventive surgical liquid jet instruments that provide a liquid cutting jet at their distal end, can be configured to effectively remove material from the surgical site and transport the material through an evacuation lumen without the need for an external source of suction for a wide variety of angular orientations between the central region of the liquid cutting jet and the longitudinal axis of the evacuation lumen. The term "central region of the liquid jet" as used herein refers to a region defining a geometric center of the liquid jet. This region is typically an essentially cylindrical region of the liquid jet confined within a cylinder whose outer surfaces are shaped and whose perimeter is defined by the inner circumference of the liquid jet opening in the nozzle, which circumference is projected from the liquid jet opening to the jet-receiving opening along an axis that is co-linear with the longitudinal axis of the jet nozzle. The "longitudinal axis" of the jet nozzle, as will be described in more detail below, is defined by the axial center line of the nozzle region of the pressure lumen. The "longitudinal axis" of the evacuation lumen refers to an axis defining the geometric center of the evacuation lumen in a region that is proximal to the jet-receiving opening. As used herein in the context of describing geometric relationships between longitudinal axes of various components, the term "co-linear" refers to components whose longitudinal axes are superimposed on essentially the same line and space. The term "parallel" when used in the same context refers to longitudinal axes that are not necessarily co-linear, but that are oriented in an essentially identical direction in space. Accordingly, surgical instruments provided according to certain embodiments of the invention enable effective evacuation of material and debris from the surgical site via a liquid cutting jet evacuation lumen, without the need for an external source of vacuum connected in fluid communication with such lumen, for a wide variety of liquid cutting jet angular configurations, including instruments providing liquid cutting jets that are directed axially, transversely, or at any angle between 0 and 180° with respect to a longitudinal axis defining the proximal end or body of the surgical instrument.

For embodiments involving surgical instruments including an evacuation lumen for receiving a liquid cutting jet, plugging of the evacuation lumen can be prevented by constructing the evacuation lumen receiving the liquid cutting jet to have a region that is

Components constructed and arranged for contact with tissue can be components that are comprised by the distal end of the rotatable shaft itself or, alternatively, can be components that are removably attachable/connectable to the distal end of the rotatable shaft. Such components may, as apparent to those of ordinary skill in the art, be provided in a wide variety of forms for performing a wide variety of functions useful in various surgical procedures. For example, in some embodiments, the component can be constructed and arranged to cut, grind, ablate, shape, drill, bore, pulverize, polish, liquefy, screw, etc., a tissue within the operating field. In addition, as described in more detail below, the rotatable shaft can be permanently, or semi-permanently, contained within the surgical instrument or, alternatively and more preferably, can be configured to be removable and exchangeable with other rotatable shafts, for example those having different components at their distal ends for performing different surgical functions. It is also contemplated that the rotatable shaft can be configured within the surgical instrument so that its distal end, including the component constructed and arranged for contact with tissue, is selectively retractable so that, under control of an operator, the distal end of the rotatable shaft may be selectively deployed into the surgical operating field for performing a surgical procedure and, when the procedure is completed, retracted into the instrument and away from the surgical field. Such a retractable configuration can be especially useful for instruments including both a rotatable shaft and a liquid cutting jet at the distal end of the instrument, wherein during a surgical procedure requiring the rotatable shaft, the shaft may be deployed into the surgical operating field, but during a procedure requiring use of only the liquid cutting jet, the rotatable shaft may be withdrawn from the surgical field, if desired.

For instruments provided according to the invention including a rotatable shaft therein, the proximal end of the rotatable shaft is typically disposed within a body or at a user-controllable proximal end of the instrument. The proximal end of the shaft is drivingly coupled to a mechanism that is constructed and arranged to impart a rotating motion to the rotatable shaft. The term “drivingly coupled” as used herein refers to the shaft being interconnected with a drive mechanism such that motion of a component of the drive mechanism imparts rotational motion to the rotatable shaft. Such coupling can be accomplished, as would be apparent to those of ordinary skill in the art, by a variety of means such as, but not limited to, gear drives, belt drives, chain drives, friction drives, etc. The drive mechanism utilized to rotate the rotatable shaft within the instrument can comprise one or more of a variety of drive mechanisms including, but not limited to, electric motors, below, an evacuation lumen including a jet-receiving opening therein is positioned opposite the jet opening in the nozzle of the rotor-driving pressure lumen and downstream of the impacting surface of the rotatable rotor so that it receives and evacuates the liquid comprising the rotor-driving liquid jet. Similarly to the evacuation lumen utilized for receiving and evacuating liquid cutting jets described above, the evacuation lumen utilized for receiving and evacuating the rotor-driving liquid jet can, in some embodiments, be placed in fluid communication with an external source of suction or can, in more preferred embodiments, be configured to enable evacuation of essentially all of the liquid comprising the liquid rotor-driving jet without the need for an external source of suction connected thereto. Except as specifically described below, the configurations useful for the nozzle and evacuation lumen utilized in the inventive rotor-driving mechanism can be similar to those described below for forming and evacuating a liquid cutting jet.

The preferred liquid jet-driven rotatable rotor described above utilizes primarily the impulse force resulting from a change in the momentum of the liquid jet, upon contact with an impacting surface of the rotor, to impart rotational motion to the rotor. In the inventive configuration, liquid leaves the nozzle of the pressure lumen as a jet having a free-surface, at the jet opening, in the surrounding gaseous environment. In such configuration, essentially the entire pressure drop of the liquid comprising the jet to atmospheric pressure takes place within the nozzle. By contrast, typical prior art fluid-driven drive mechanisms for use in surgical devices employ a turbine-driving fluid stream that is confined within a channel and utilize the acceleration of the fluid, while it is in contact with a turbine or rotor, characterized by a change in the hydrostatic pressure of the fluid while in contact with the turbine/rotor, to drive rotation of the turbine/rotor. The present inventors have determined that the preferred liquid jet-driven rotor mechanism provided according to the invention can, under certain conditions, provide improved efficiency of operation as well as improved torque vs. load characteristics, as compared with prior art mechanisms.

Also, as described in more detail below, for many embodiments of the invention, it is often desirable to provide a mechanism for drivingly coupling a liquid jet-driven rotor to a rotatable shaft of a surgical instrument so that the rotational speed of the rotatable shaft is different from that of the rotational speed of the liquid jet-driven rotor. Such rotational speed-changing drive mechanisms are well know to those of ordinary skill in the art. In the context of the present invention, a preferred drive coupling mechanism utilizes a gear reduction drive. The gear reduction drives utilized according to the invention can be utilized, as apparent to those of ordinary skill in the art, for example, such means including but not limited to, ultrasound welding, snap fitting, solvent welding, etc.

Surgical instrument 100 has a distal end 116 including a pressure lumen 118 and an evacuation lumen 120. Distal end 116 of instrument 100 further includes a rotatable grinding burr 122 disposed at the distal end of a rotatable shaft 124 (seen more clearly in FIG. 2A). "Distal end" when used herein in the context of a region of a surgical instrument refers to a portion of a surgical instrument that is adapted to perform a surgical procedure on a patient and which is inserted into a surgical field during operation of the instrument. The distal end 116 of instrument 100 can, in some embodiments, comprise only the distal ends 126, 128 of pressure lumen 118 and evacuation lumen 120 respectively as well as the distal end 130 of rotatable shaft 124 (see FIG. 2A) including grinding burr 122. In other embodiments, distal end 116 of instrument 100 can also include components proximal to the distal ends of the pressure lumen, evacuation lumen, and rotatable shaft that are also inserted into a surgical operating field of a patient during operation of the instrument. In addition, in other embodiments, not shown, the instrument may provide only a rotatable shaft and may not include a pressure lumen and an evacuation lumen at the distal end of the instrument. In yet other embodiments, the instrument may not include a rotatable shaft and grinding burr as shown but may instead include only a pressure lumen at the distal end of the instrument or, in other embodiments, a pressure lumen together with a target or evacuation lumen positioned opposite the pressure lumen to receive a liquid cutting jet.

In the illustrated embodiment, surgical instrument 100 further includes a sheath 132 which at least partially surrounds pressure lumen 118, evacuation lumen 120, and rotatable shaft 124. As explained in more detail below, sheath 132 aids in supplying support for the lumen to assist in maintaining and/or establishing a desired geometric configuration between pressure lumen 118 and evacuation lumen 120 to prevent relative motion of the lumen and misdirection of a liquid cutting jet. In addition, sheath 132 can be used for providing support and evacuation to distal end 130 of rotatable shaft 124. As discussed in more detail below in the context of FIGs. 2A-2C, removably coupled to distal end 116 and sheath 132 is burr tip support 136 including a snap tab 138 which fits into snap-lock slot 140 on sheath 132 to enable removable coupling thereto. Burr tip support 136 also serves to provide a bearing surface for distal end 130 of rotatable shaft 124, as well as to provide support to pressure lumen 118 and evacuation lumen 120.

has an inlet 182 coupled to high pressure liquid supply conduit 184 by means of a manually tightenable high pressure tubing coupling 186. Valve 180 also includes a first outlet 188 that is coupled via high pressure connector 190 to pressure lumen 118 supplying high pressure liquid to nozzle 192 disposed at distal end 116 of the instrument for forming a liquid cutting jet. Valve 180 also includes a second outlet 194 coupled via high pressure connector 196 to pressure lumen 164 supplying high pressure liquid to rotatable shaft drive mechanism 152. Liquid flow directing valve 180 can be manually adjusted by an operator, via sliding motion of knobs 197, which are coupled to a shaft 198 (see FIG. 12), to enable liquid supplied via conduit 184 to be directed to either pressure lumen 118 or pressure lumen 164, depending upon the position of knobs 197, or to be directed to both pressure lumens simultaneously.

High pressure connectors 186, 190, and 196 may comprise any type of suitable high pressure connection known to those of ordinary skill in the art that is capable of withstanding, for example, pressures in excess of 1,000 psig, and preferably is capable of withstanding pressures up to at least about 50,000 psig. Such connectors may comprise welded/brazed fittings, flanged fittings, swaged fittings, etc., as apparent to those of ordinary skill in the art. In a preferred embodiment, as illustrated, the high pressure fittings utilized include highly compressed elastomeric O-rings and are configured as described in commonly owned U.S. Patent No. 5,713,878, incorporated herein by reference.

FIG. 2A is an exploded perspective view of the portions of surgical instrument 100 disposed distal to body 104. As illustrated in FIG. 2A, rotatable shaft 124, pressure lumen 118 and evacuation lumen 120 are shown removed from sheath 132 for clarity. Pressure lumen 118 and evacuation lumen 120 are preferably constructed from a surgical grade stainless steel, however, in alternative embodiments, either or both of the lumen may be constructed from other suitable materials, for example certain polymeric materials, as apparent to those of ordinary skill in the art. Regardless of the specific material from which the pressure lumen is constructed, pressure lumen 118 (as well as pressure lumen 164 supplying drive mechanism 152) must have sufficient burst strength to enable the lumen to conduct a high pressure liquid to the nozzle, for example nozzle 192, at the distal end of the pressure lumen in order to form a liquid jet. The burst strength of the pressure lumen utilized in the surgical instrument should be selected to meet and preferably exceed the highest contemplated pressure required for use in the specific surgical procedure to be performed. Typically, surgical instrument 100 will operate at liquid pressures of between about 500 psig and about 50,000 psig, depending on the intended material to be cut and/or ablated and/or the performing a surgical function on tissue of a patient can be interchanged during the course of a procedure or between surgical procedures. Replacement or exchange of a rotatable shaft/burr element can be performed as follows. While in an assembled configuration, for example as shown in FIG. 1, the user depresses snap tab 138 on the spring flange region 220 of burr tip support 136 and slides the burr tip support and rotatable shaft from bore 222 of sheath 132. Pressure lumen 118 and evacuation lumen 120 are rigidly connected at their proximal ends within body 104 of instrument 100 and remain within the sheath during removal of the rotatable shaft and burr tip support. While removing burr tip support 136 from sheath 132, the distal ends of pressure lumen 118 and 120 slide through pressure lumen slot 216, including a nozzle slot 224 therein, and evacuation lumen slot 214. Upon removal of burr tip support 136 and rotatable shaft 124, upper support member 210 and lower support member 212 can be separated, rotatable shaft 124 can be exchanged with another rotatable shaft having, for example, a different component at a distal end thereof, the upper support and lower support can be reassembled, and the burr tip support/rotatable shaft unit can be re-inserted into bore 222 of sheath 132 until snap tab 138 snaps into snap lock slot 140 of the sheath, thus completing the exchange process. Those of ordinary skill in the art will readily envision a variety of alternative means for providing exchangeability of rotatable shaft 124 of instrument 100, all of which are deemed to be within the scope of the present invention.

Upon assembly, burr tip support 136, in addition to providing a distal bearing for rotatable shaft 124, also supplies support for pressure lumen 118 and evacuation lumen 120 to assist in maintaining and/or establishing a desired geometric configuration between the pressure lumen and the evacuation lumen when instrument 100 is in operation. In preferred embodiments, pressure lumen 118 and evacuation lumen 120 are supported by burr tip support 136, when the instrument is assembled, so that the distal ends of the lumen are sufficiently stiff to prevent deflection of the lumen, by, for example, contact with surfaces within the surgical operating space, which deflection could potentially lead to misdirection of the liquid cutting jet formed by nozzle 192 as high pressure liquid flows therethrough so that the cutting jet is no longer incident upon jet-receiving opening 193 in evacuation lumen 120, thus potentially causing unintended tissue damage to the patient.

FIG. 3 is a perspective view showing surgical instrument 100 as viewed from a proximal end thereof. FIG. 3 illustrates the assembled surgical instrument except excluding body 104 to show the internal components with greater clarity. The particular view illustrated shows more clearly the back view of shaft drive mechanism 152 showing shaft therein to form a continuous, leak-tight path for fluid communication between shaft evacuation conduit 174 and evacuation channel slots 218 of burr tip support 136, when the instrument is assembled as shown in FIGs. 1 and 2A-2C. In the illustrated embodiment, evacuation is supplied to the distal end of the instrument surrounding grinding burr 122 by coupling shaft evacuation conduit 174 in fluid communication with a source of external suction, such as a suction pump or aspirator. As described below, in alternative embodiments, rotatable shaft 124 can be configured such that rotation of the shaft is able to impart a driving force for removing material from the region surrounding the grinding burr without requiring conduit 174 to be attached to the source of external suction.

Collar 144 further includes a centrally disposed cavity 242 therein having a distal region 244, which is conically tapered, and a proximal region 246, which is essentially cylindrical in shape. Distal end 248 of rotor housing base 162 is shaped to mate with inner sealing surfaces 250 of cavity 242 in collar 144, to create a vacuum-tight seal between surface 252 of the distal end of the bearing block and inner sealing surface 250 of the collar.

Distal end 248 of rotor housing base 162 includes grooves 254, 256 machined therein, which grooves form channels for passage of pressure lumen 118 and evacuation lumen 120 respectively. In order to prevent leakage of evacuated fluid and a loss of suction through grooves 254 and 256 during operation of the device, a bead of sealant 258 can be used to surround the lumen and create a vacuum-tight seal with inner sealing surface 250 of collar 144, upon assembly of the device. Such sealant can be comprised of a polymeric foam or RTV sealant, as would be apparent to those of ordinary skill in the art.

Proximal end 248 of rotor housing base 162 further includes a sheath evacuation channel 260 machined therein for providing a fluid flow path for transport of fluid and debris between cavity 262, comprising a sheath evacuation region, and evacuation conduit 174. During operation of the device, when a suction is applied to evacuation conduit 174, liquid and debris will flow into sheath 132 via evacuation channel slots 218 of burr tip support 136, then through bore 240 of collar 144 into sheath evacuation cavity 262, through sheath evacuation channel 260, and finally through evacuation conduit 174 for removal from the instrument.

Also shown in FIG. 4 are rotor jet pressure lumen mounting blocks 264, 266 which are utilized to mount rotor drive pressure lumen 164 to rotor housing block 160 via, for example, screws 268. As described in more detail below, the rotor jet pressure lumen mounting blocks enabled precise alignment and direction of the liquid jet formed by the axis 298 of pressure lumen 284. Specifically, nozzle region 292 is bent with respect to longitudinal axis 298 of pressure lumen 284 outside of jet nozzle region 292, so that jet opening 294 emits a liquid jet 296 whose central region is directed along an axis 300 that is essentially perpendicular to longitudinal axis 298. In alternative embodiments, the angle formed between jet axis 300 and longitudinal axis 298 can be any angle between about 0° and about 90° (as shown).

Nozzles provided according to the invention, both for forming liquid cutting jets and for forming liquid jets to drive rotational components of the instruments (as described in more detail below) preferably have a relatively large nozzle length to internal diameter ratio. The nozzles for use in inventive surgical instruments, both for forming liquid cutting jets and for driving rotational motion of a rotatable shaft, preferably have a region having a minimum internal diameter, which region has a length that exceeds its minimum internal diameter by at least a factor of about 2, more preferably by a factor of about 4, and even more preferably by at least a factor of about 6. In other embodiments, the region has a length that exceeds its minimum internal diameter by at least a factor of about 10. As will be discussed in more detail below, the greater the ratio of the length to minimum internal diameter of the nozzle region, the more narrowly focused and collimated will be the liquid jet that is emitted from the jet opening of the nozzle. For reasons described in more detail below, highly collimated liquid jets are preferred both for forming liquid cutting jets at the distal end of the inventive surgical instruments and for driving rotational motion of rotatable rotors and shafts provided by the inventive surgical instruments. However, in general, nozzles with ratios of length to minimum internal diameter that are very high, for example greater than about 10, tend to create a very high pressure drop through the nozzle during use without significantly improving the degree of collimation of the jet and, therefore, are less preferred for use in the inventive surgical instruments than nozzles having a ratio of length to minimum internal diameter of an intermediate value, for example about 6.

The present invention provides surgical liquid jet instruments which are specifically designed and constructed for use in a particular surgical environment. Specifically, certain embodiments of the invention provide surgical liquid jet instrument designs that are tailored to provide highly desirable liquid jet cutting characteristics in surgical operating environments where the liquid jet is submerged in a liquid environment when the instrument is in operation. More specifically, the invention provides, in such embodiments, surgical liquid jet instruments including pressure lumen and evacuation lumen that are shaped, and internal diameter of between about 0.001 and about 0.02 inches, more preferably between about 0.003 and about 0.01 inches, and most preferably about 0.005 inches.

Liquid cutting jet 296, which is collimated as it exits jet opening 294, tends to create a visible, opaque entrainment region 302 surrounding liquid cutting jet 296. Entrainment region 302 is comprised of rapidly moving liquid, which is entrained and driven by the kinetic energy of liquid cutting jet 296. Liquid cutting jet 296, as it rapidly moves through liquid environment 300, also tends to create a zone of low pressure, which is essentially coextensive with entrainment region 302. In typical embodiments involving high pressure liquids and rapidly moving liquid jets, the pressure in entrainment region/low pressure zone 302 will be lower than the vapor pressure of the surrounding liquid in liquid environment 300, thus causing cavitation of the liquid in entrainment region 302 and a resulting formation of an abundance of extremely small gas bubbles 304 within the liquid in the entrainment region 302, making the region visually opaque.

As discussed previously, it is desired, in preferred embodiments, for safety and performance that the instrument be designed to reduce, and preferably eliminate, undesirable effects, such as blow-by of the liquid jet, plugging of the jet-receiving opening and the evacuation lumen, and inefficient tissue/debris entrainment and removal. Also, as previously mentioned, in preferred embodiments, it is desirable that ablated tissue and debris be evacuated from the surgical site through the evacuation lumen, without the need for a source of external suction to be applied to the proximal end of the evacuation lumen. In order to provide the above-mentioned characteristics, the inventive surgical instruments for use in a liquid environment can include an evacuation lumen having specifically selected predetermined shapes and configurations, which is positionable relative to the jet opening at a specific predetermined distance. Specifically, in preferred embodiments, jet-receiving opening 193 is positioned, when the instrument is in operation, opposite jet opening 294, at a predetermined distance ℓ therefrom, and provided in a nozzle 192 having a length to minimum diameter ratio so that essentially all of the fluid in liquid cutting jet 296 enters jet-receiving opening 193. As discussed above, liquid cutting jet 296 will tend to create entrainment region 302 surrounding the liquid cutting jet 296 when the instrument is in operation. Entrainment region 302 will typically be symmetrically deposed around liquid cutting jet 296 and will tend to diverge in a direction from jet opening 294 to jet-receiving opening 193. In typical embodiments where jet opening 294 is circular in shape, entrainment region 302 will have a truncated cone shape, having a truncated apex at jet opening 294 and a instruments intended to be operated in a liquid environment include a maceration region 306 within and/or downstream and in close proximity to the inlet to evacuation lumen 120 at jet-receiving opening 193. Maceration region 306 is defined as a region that contains a liquid undergoing intensely turbulent flow and impacting an internal surface of the evacuation lumen at an acute angle, thus creating significant impacting forces capable of macerating entrained material/tissue, when the instrument is in operation. The combination of the intensely turbulent flow of the liquid in maceration region 306 and the impacting forces of liquid cutting jet 296 and the liquid in entrainment region 302 against the wall of evacuation lumen 120 enable the liquid within the maceration region to macerate at least a portion of any tissue or material entrained by the liquid in entrainment region 302 into a plurality of small particles. In preferred embodiments, the maceration region is able to macerate a substantial fraction (i.e., the majority of) the entrained tissue into a plurality of small particles. In most preferred embodiments, the plurality of particles at least partially comprises a plurality of microscopic particles too small to be seen unaided with the human eye. In all cases, the particles should be small enough to pass through evacuation lumen 120 without plugging the evacuation lumen, when the instrument is in operation.

In order to provide a maceration region, evacuation lumen 120 preferably includes a jet-deflecting portion 308 that is located adjacent to and downstream of jet-receiving opening 193. Jet-deflecting region 308 may be either a straight surface that is angled with respect to the direction of at least a central portion of liquid cutting jet 296, or in preferred embodiments, jet-deflecting region 308 comprises a smoothly curved surface upon which at least a portion of liquid cutting jet 296 impinges, where the curved surface is shaped to deflect at least a portion, and preferably all of the liquid cutting jet 296 and liquid comprising entrainment region 302 in a direction that is essentially parallel to the longitudinal axis 312 of evacuation lumen 120 in the region proximal to the jet-deflecting region 308. In preferred embodiments, the radius of curvature of the curved surface defining jet-deflecting region 308 is essentially constant, having a value of between about 0.5 and about 20 times the internal diameter of evacuation lumen 120. In one preferred embodiment, the radius of curvature of the curved surface defining jet-deflecting region 308 is essentially equal to the internal diameter of evacuation lumen 120 at jet-deflecting region 308, so that essentially no portion of jet-receiving opening 193 projects radially beyond a perimeter defined by an outer surface 314 of a portion of the evacuation lumen located proximal and adjacent to jet-deflecting region 308. It is also generally preferable for the surgical instruments provided by the preferred embodiments, the cross-sectional area of constriction 322 should be between about three and about eight times the cross-sectional area of jet-opening 294 in nozzle 192.

Referring again to FIG. 6A, evacuation lumen 120 is shaped and positioned relative to pressure lumen 118 so that at least a central portion of liquid cutting jet 296 is directed into jet-receiving opening 193 in a direction forming a non-zero angle with respect to (i.e. non-parallel with) the longitudinal axis 312 of evacuation lumen 120 in a region proximal to jet-deflecting region 308. In some embodiments, this angle can be between about 45 degrees and about 115 degrees, in other embodiments between about 80 degrees and about 100 degrees, and in some preferred embodiments, as illustrated, the angle can be about 90 degrees.

As described above, in some embodiments of the invention involving surgical instruments including rotatable shafts, liquid and debris surrounding a grinding burr, or other tissue contacting component at a distal end of the rotatable shaft, can be evacuated by coupling a sheath of the instrument surrounding the rotatable shaft to a source of external vacuum or suction. In other embodiments, also as mentioned above, rotation of the rotatable shaft itself may be utilized to generate an evacuating force for removing liquid and debris from an area surrounding the distal end of the rotatable shaft. FIG. 7A shows a partial section of a distal region of rotatable shaft 400 that is constructed and arranged to generate an evacuation force tending to drive liquid and debris from the distal end of a sheath surrounding shaft 400, when it is assembled within a surgical instrument according to the invention, to the proximal end of such sheath. "Constructed and arranged to generate an evacuation force" as used herein in the present context refers to the ability of a rotatable shaft, rotating either within a surrounding sheath or without a surrounding sheath, to be able to drive liquid from a region near the distal end of the rotatable shaft towards the proximal end of the rotatable shaft and out of a surgical field into which a distal end of the rotatable shaft is placed, without the need for an external source of suction.

In operation, rotatable shaft 400 rotates in a direction shown by arrow 402. Rotatable shaft 400 includes a portion 404 of increased cross sectional dimension, preferably having a cross sectional dimension only slightly less than an internal cross sectional dimension of a surrounding sheath in which rotatable shaft 400 is disposed when assembled into a surgical instrument. Region 404 includes a helically grooved channel 406 machined therein. Both region 404 and channel 406 are positioned on shaft 400 so that they are surrounded by a sheath when assembled into a surgical instrument. Rotation of shaft 400 in the direction of evacuation force created by the rotating shaft may also be used to create an evacuation force tending to evacuate other regions of the surgical instrument, for example regions of the housing containing the drive mechanism for the rotatable shaft.

FIG. 8A shows an exploded perspective view of one preferred embodiment for rotatable shaft drive mechanism 152. Rotatable shaft drive mechanism 152 includes a liquid jet-driven rotatable rotor 450, which in the embodiment illustrated in FIG. 8A comprises a saw-tooth rotor. Upon assembly of the three subcomponents of rotor housing 154 (i.e., rotor cap 158, rotor housing block 160 and rotor housing bottom 162), rotatable rotor 450 is contained and rotates within a rotor slot 452 included in rotor housing block 160 and rotor housing cap 158. Rotatable rotor assembly 454 includes, in addition to rotatable rotor 450, rotor bearings 172 and 456 disposed at each end of a central shaft 458, upon which the assembly rotates. Bearings 172 and 456 are held within flanges 460 and 462 upon assembly of the rotor housing.

Rotor assembly 454, in the illustrated embodiment, also includes a worm gear 464 which mates with a complementary worm wheel 466 located on rotatable shaft drive assembly 468 (shown more clearly in an assembled state in FIG. 8B). Gear reduction mechanisms utilizing worm gears, such as illustrated in FIG. 8A, are preferred for some embodiments because they provide relatively high gear reduction ratios for their size. In other embodiments, where a lower degree of gear reduction and a lower difference in rotational speed between rotatable rotor 450 and drive shaft 470 of rotatable shaft drive assembly 468 is required or desired, other means of gear reduction, for example spur gears, helical gears, or any other suitable gear reduction mechanisms apparent to those of ordinary skill in the art can be utilized. In addition, for embodiments where high speeds are required or desired or only low torques are necessary during operation, the gear reduction mechanism may be eliminated entirely and the rotatable rotor assembly 454 may be utilized to drive rotatable shaft 124 directly. In such an embodiment, rotatable shaft drive mechanism 152 could dispense entirely with rotatable shaft drive assembly 468, and instead couple the rotatable shaft 124 directly to rotatable rotor assembly 454. Of course, in such embodiments, it is desirable to position rotatable rotor assembly 454 so that its longitudinal axis 472 is aligned parallel to longitudinal axis of rotatable shaft 124 (i.e., it would be desirable to orient rotatable rotor assembly 452 in the orientation currently shown for rotatable shaft drive assembly 468 in FIG. 8A).

the mechanism, to prevent submersion of rotatable rotor or the rotatable components in liquid, when the instrument is in operation.

FIG. 8B is a perspective view of rotatable rotor assembly 454 and rotatable shaft drive assembly 468 as they are coupled upon assembly of rotatable shaft drive mechanism 152. As shown in FIG. 8B, the various housing components have been eliminated to show assemblies 454 and 468 with greater clarity. As is shown in the figure, for embodiments having a drive mechanism including gear reduction (e.g., provided by worm gear 464 and worm wheel 466 as illustrated) it is preferred to align rotatable rotor assembly 452 such that its longitudinal axis 472 is essentially perpendicular to longitudinal axis 496 of rotatable shaft drive assembly 468.

As will be apparent to those of ordinary skill in the art, the particular rotational speeds of rotor 450, rotor drive assembly 454, and drive shaft 470 of rotatable rotor drive assembly 468 must be selected based upon the needs of the particular surgical application and on the characteristics of the particular rotatable component being utilized for tissue contact and being rotated by the rotatable shaft. For typical applications utilizing the inventive surgical instruments, the rotational speed of rotatable rotor 450 will be at least about 16,000 RPM, in other embodiments at least about 65,000 RPM, in yet other embodiments at least about 130,000 RPM, in yet other embodiments at least about 250,000 RPM, and in still other embodiments at least about 500,000 RPM. The diameter of rotatable rotor 450 is typically at least about 0.5 inch, in other embodiments at least about 1 inch, in other embodiments at least about 2 inches, in other embodiments at least about 5 inches, and in yet other embodiments at least about 10 inches. The gear reduction mechanism is selected and configured in preferred embodiments, so that the rotational speed of rotatable rotor 450 will exceed the rotational speed of drive shaft 470 of rotatable rotor drive assembly 468. In typical embodiments, the rotational speed of rotatable rotor 450 will exceed that of drive shaft 470 by at least about a factor of 2, in other embodiments by at least about a factor of 5, in other embodiments by at least about a factor of 10, in other embodiments by at least about a factor of 20, and in yet other embodiments by at least about a factor of 30. In one particularly preferred embodiment involving a surgical instrument including a rotatable shaft having a 5 mm diameter fluted burr at a distal end thereof , which is utilized for bone grinding in a surgical operating field, rotatable rotor 450 comprises a 1 inch diameter saw-tooth rotor having between about 10 and 200 teeth, and in one preferred embodiment about 80 teeth, which is driven at a rotational speed during operation of about 130,000 RPM and is coupled to drive shaft 470 via a worm-other words, the above parameters are preferably selected so that at the point of impact 506 of liquid jet 502 with an impacting surface 500, the cross-section of liquid jet 502, within the plane of impacting surface 500, is essentially entirely incident on impacting surface 500 so that essentially no part of the liquid jet "misses" or "blows by" the impacting surface. In such a situation, the momentum of the entire liquid jet can potentially be imparted to rotatable rotor 450 to create rotational motion of the rotor.

The distal end of rotor jet evacuation lumen 166 is shown partially cutaway in Fig. 8C to more clearly show nozzle 490, liquid jet 502, and rotatable rotor 450, as positioned within the distal end of the lumen. As shown more clearly in Figs. 8D and 8E, the distal end of evacuation lumen 166, which is disposed within rotor housing block 160 upon assembly of rotatable shaft drive mechanism 152, includes a slit 504 in which a portion of rotatable rotor 450 is located during operation. Furthermore, the distal end of pressure lumen 164 including nozzle 490 is also positioned within and essentially completely surrounded by the distal end of evacuation lumen 166 when the drive mechanism is assembled. This configuration serves to maximize the containment of any spray that is created upon the impacting of liquid jet 502 with an impacting surface 500 of rotatable rotor 450. This is especially important for periods of operation of the instrument where the rotatable shaft of the instrument is subjected to significant torque tending to inhibit its rotation. During such periods of operation, rotatable rotor 450 will tend to rotate at a speed that is less than the velocity of liquid jet 502. Under such conditions, liquid jet 502 can have a tendency to form spray or mist upon impacting an impacting surface 500. By contrast, under conditions of free rotation, rotatable rotor 500 rotates at a speed essentially equal to the speed of liquid jet 502, so that the trajectory of liquid jet 502 remains essentially constant even after impacting an impacting surface 500, and minimal spray is created. In an alternative embodiment, the evacuation lumen can be configured and positioned so that it does not surround and enclose any portion of the distal end of pressure lumen but, instead, is positioned distally of the nozzle in the pressure lumen, preferably with a jet-receiving opening positioned within about 0.01 inch of the jet opening in the nozzle.

The design of evacuation lumen 166 as illustrated enables effective evacuation of essentially all of the liquid comprising liquid jet 502 from the housing enclosing the rotatable rotor assembly during operation of the device under a wide range of loads and resistances applied to the rotatable shaft of the instrument. In certain embodiments, the proximal end of evacuation lumen 166 can be placed in fluid communication with a source of external suction

500 so that it is also essentially perpendicular to the surface as measured in the y-z plane, illustrated in FIG. 9A. In other embodiments, the liquid jet can be directed along liquid jet direction 510, such that the liquid jet is directed toward surface 500 at a relatively small angle as measured within the y-z plane so that the liquid jet is angled somewhat to impinge closer to the base 514 of saw tooth 498. The term "essentially perpendicular," when used in the context of describing the direction of a liquid jet with respect to an impacting surface of a rotatable rotor, refers to the liquid jet being directed towards the impacting surface of the rotatable rotor such that it is essentially perpendicular to the surface in at least the x-z plane as illustrated in FIG. 9B.

Preferred saw tooth rotors have liquid jet impacting surfaces that are essentially planar. Furthermore, as described above in the preceding paragraph, the surfaces are preferably oriented with respect to the rotor such that each impacting surface is oriented essentially perpendicularly (or is essentially perpendicular to) a liquid jet impacting thereon at at least one rotational position of the rotatable rotor. Furthermore, in preferred embodiments, each liquid jet impacting surface 500 of rotatable rotor 450 is also oriented at an angle of between about 75 degrees and about 105 degrees with respect to a line 516 tangent to the circle circumscribed by the outermost perimeter of the rotor as it rotates about its axis of rotation 518. In some especially preferred embodiments, each liquid jet impacting surface 500 of rotatable rotor 450 is oriented essentially perpendicularly to line 516

In alternative embodiments, a rotor having liquid jet impacting surfaces that are curved may be utilized in place of a saw tooth rotor having planar impacting surfaces, as previously described. FIG. 10A shows a perspective view of a curved-vane rotor 520 having curved liquid jet impacting surfaces 522. Curved impacting surfaces 522 are defined by a series of curved vanes 524 positioned along the periphery of rotor 520. As illustrated, preferred curved-vane rotors have impacting surfaces 522 that are oriented to provide an impacting surface that is concave with respect to the direction of an incoming liquid jet, shown by arrow 526. In the illustrated embodiment, curved impacting surfaces 522 comprise semi-cylindrical surfaces. For embodiments utilizing rotors having smoothly curved liquid jet impacting surfaces 522, it is preferred for the liquid jet to be oriented in a direction 526 such that it is directed toward surface 522 essentially tangentially to the surface.

FIG. 10B illustrates a particularly preferred configuration for orienting and positioning curved vanes 524 around the periphery of rotor 520. As illustrated in FIG. 10B, in a preferred embodiment, angle α formed between the line 523 tangent to impacting surface connecting the exhaust lumen/conduits in the manner shown in FIG. 11A outside of the body of the surgical instrument (as would be the case if using surgical instrument 100 as illustrated in Fig. 1 above); however, in other embodiments, manifold 534 can be configured to and contained within the body of the surgical instrument.

FIG. 11B shows an alternative embodiment for a surgical fluid jet instrument that includes a rotatable shaft configured to create an evacuation force upon rotation of the shaft, as previously described in FIGs. 7A-7C. With such a configuration, the external source of suction can be eliminated entirely, and the entire surgical instrument can be configured to be self-evacuating without the need for an external source of suction. In the illustrated embodiment, the various evacuation lumen and conduits are connected to a manifold 542. In the illustrated embodiment, the liquid momentum supplied by the eductor pump action of rotor jet evacuation lumen 166 and liquid cutting jet evacuation lumen 120 are utilized in combination with the liquid motive force supplied by the rotatable shaft through sheath 132 to create a sufficient suction in manifold 542 to evacuate evacuation conduit 168 connected to rotor housing block 160 and evacuation conduit 170 connected to the rotor housing base 162 of the surgical instrument.

A cross-sectional view showing the internal details of liquid flow directing valve 180 is illustrated in FIG. 12. Liquid flow directing valve 180 includes a valve body 550 formed of a rigid sturdy material, for example surgical grade stainless steel, having a centrally disposed bore therein forming a cylinder 552 internal to valve body 550. Valve 180 is configured as a slidable three-way valve. Valve body 550 further includes an inlet 182 comprising a bore having threaded walls configured to mate with a high pressure tubing coupling 186 (shown in FIG. 1). Similarly, valve body 550 further includes a first 188 and a second 194 outlet configured with internally threaded surfaces for coupling to high pressure connectors 190 and 196 respectively.

Disposed within centrally disposed cylinder 552 is a shaft 554, preferably comprised of a rigid, durable metal such as surgical grade stainless steel, connected by threads 555 at each end to user actuated knobs 197. Also disposed on shaft 554 are two elements 556 comprising pressure tight sealing components for preventing leakage of high pressure liquid from and within valve 180. Elements 556 comprising the pressure tight sealing components are described in greater detail below in the context of FIGs. 13A and 13B. Elements 556, while shown for use within the context of liquid flow directing valve 180, can also be used for a wide variety of other applications where a high pressure, slidable sealing component is leftmost range of travel. In this configuration, high pressure liquid would flow from inlet 182 through flow channel 564 and out of the valve through outlet 194, which is in fluid communication with rotor drive pressure lumen 164. This configuration can be utilized for driving a liquid jet-driven rotatable shaft of the instrument without simultaneously creating a liquid cutting jet with the instrument. Yet a third user-selectable position, in some embodiments, can be achieved by positioning shaft 554 at a position roughly equidistant between its rightmost and leftmost ranges of travel. In this third user-selectable position, high pressure liquid will flow from inlet 182 through flow channel 564 and out of the valve through both outlets 188 and 194. In this configuration, the user may create a liquid cutting jet with the instrument while simultaneously powering a liquid jet-driven rotational shaft of the instrument.

Elements 556 are shown in greater detail in FIG 13. Element 556 is configured as a pressure-tight sealing component. A "pressure-tight sealing component" as used herein refers to a component that is able to form a pressure-tight seal between two regions of a cylinder, each containing a fluid therein, wherein the fluids contained in the two regions are at different hydrostatic fluid pressures. A "fluid" when in the present context can comprise a liquid, gas, supercritical fluid, slurry, suspension, or any mixture of the above, and refers to the thermodynamic state of the material present in the regions of the cylinder at the temperature and pressure at which the component is used in operation. In the context of use of the pressure-tight sealing component within liquid flow control valve 180, the fluid contained in at least one of the above-mentioned regions of the cylinder will comprise a liquid; however, as apparent to those of ordinary skill in the art, element 556 can also be used for a wide variety of other pressure sealing applications not necessarily involving pressurized liquids.

Element 556 is shown in cross section of Fig. 13 together with a portion of spacer 558. Shaft 554 has been removed in the figure to show the illustrated components with greater clarity. Element 556 may be comprised of a wide variety of materials capable of withstanding the pressures contemplated, such as, for example, a variety of metals, ceramics, plastics, etc. Element 556 is, in preferred embodiments, comprised of a non-elastomeric, semi-rigid plastic that is dimensionally stable within the range of operating pressures contemplated. Preferred plastics include crystalline polymers or semi-crystalline polymers, or amorphous polymers having a glass transition temperature higher than the operating temperature of the apparatus utilizing element 556 as a sealing component. Element 556 can be constructed from a wide variety of engineering plastics, for example, of element 556 is formed integral to surface 565 abutting spacer 558. Surface 565 also includes a ridge 566 for seating against angled internal surface 568 of spacer 558. In other embodiments, flared sealing flange portion 559 may be located along main body portion 563 at a position intermediate spacer abutting surface 565 and knob abutting surface 570. It should also be understood that in other applications element 556 may be configured as a cap having surface 565 extending completely across the centrally disposed bore 572 within the interior of the element. Such a configuration could potentially be useful for use as a pressure sealing cap on the end of a shaft.

As configured for use in liquid directing valve 180, element 556 has a main body portion 563 configured with a tube-like annular shape, wherein centrally disposed bore 572 is disposed entirely through the central region of the element, permitting the element to be mounted to shaft 554, which shaft passes through centrally disposed bore 572, when the element is mounted to the shaft.

Flared sealing flange portion 559 of element 556 has a predefined length 574 and is angled to extend away from outer surface 576 of main body portion 563 and toward inner surface 560 of cylinder 552 of valve 180 when the valve is assembled. The flared sealing flange portion 559 extends away from surface 576 of main body portion 563, as shown, to form a cantilevered circumferential flange around the periphery of element 556. A "cantilevered circumferential flange" refers to a flange that circumscribes the entire outer perimeter of the main body portion of the element and is attached to the main body portion along one of its sides, while having at least two additional sides or faces (e.g., surfaces 561, 577, and 578) not attached to or integral with the main body portion of the element (i.e., having a triangular cross-sectional shape or a trapezoidal or rectangular cross-sectional shape).

Predefined length 574 and minimum thickness 580 of sealing flange portion 559 tend to vary approximately linearly with the size of cylinder 552 in which sealing element 556 is disposed during operation. In one exemplary embodiment utilizing a Delrin plastic element having a main body portion with an external diameter D_I of about 0.182 inch that is used as a pressure-tight sealing component within a cylinder having an internal diameter of about 0.1875 inch, length 574 is about 0.025 inch and thickness 580 is about 0.003 inch.

Sealing element 556 has a second outer diameter D_O defined by an outermost periphery 582 of flange portion 559 that exceeds the outer diameter D_I of main body portion 562. When element 556 is disassembled from cylinder 552 of valve 180, outer diameter D_O

located at the distal end of the instrument for placement in the surgical field during operation, which electrodes comprise an integral or attached component of the surgical instrument, such that electrocautery can be performed with the surgical instrument without the need for insertion into the surgical field of any additional instrumentation, and without the need for removal and replacement of the surgical instrument from the surgical field. Integrated electrocautery capability in certain embodiments of the inventive surgical instruments can be configured with a single positive electrode located near the distal end of the surgical instrument and can be operated in a monopolar mode. For such embodiments, the electrode provided by the instrument acts as the positive electrode and the body of a patient acts as a source of ground potential, for example via contact with a grounding pad in electrical communication with an external power supply. A "positive electrode" or "positive terminal" as used herein refers to an electrode or terminal of a surgical instrument or external power supply having an electrical potential differing from that of ground potential (0 volts). A "source of ground potential" as used herein refers to an electrode, surface, terminal, etc., that is maintained at essentially ground potential during performance of electrocautery with a surgical instrument.

Preferred surgical instruments, according to the invention, including integrated electrocautery further include at least one lumen therein able to conduct an electrically conductive liquid to the distal end of the instrument for insertion into a surgical field. Such a lumen is able to add conductive liquid to the surgical field in order to maintain an electrocautery electrode at the distal end of the instrument submerged in an electrically conductive liquid so as to enable current flow from a positive electrocautery electrode to a source of ground potential within the environment of the surgical field during electrocautery. Especially preferred instruments including integrated electrocautery include a pressure lumen therein able to conduct a high pressure liquid to the distal end of the instrument and able to form a liquid cutting jet within the surgical field. Some preferred surgical instruments will also include an exhaust lumen with a jet-receiving opening, positioned opposite a jet opening in a nozzle region of the above-mentioned pressure lumen, for evacuation of liquid and debris from the surgical field. Some preferred embodiments of surgical instruments including integrated electrocautery can also include a rotatable shaft therein for powering a tissue contacting component, for example a grinding burr. Such an instrument was described previously in the context of FIG. 1 and is shown and described, as configured with integrated electrocautery below in the context of FIGs. 16A and 16B.

other embodiments of surgical liquid jet cutting instruments described in U.S. Patent Application Serial No. 09/313,679 could be similarly configured with integrated electrocautery as provided by the current invention. As described below, in some preferred embodiments, the at least one integrated electrocautery electrode provided at the distal ends of surgical instruments according to the invention comprises at least a portion of a distal end of a lumen of the surgical instrument configured to either supply liquid to a surgical field (e.g., a pressure lumen) or withdraw liquid from a surgical field (e.g., an evacuation lumen). In some such preferred embodiments, as discussed in more detail below, electrodes are provided at the distal end of one or more lumen of the surgical instruments by selectively coating the external surface of such lumens with an essentially continuous layer of an electrical insulator, while leaving certain regions the lumen uncoated, which uncoated regions providing an electrode surface. An "essentially continuous layer" of electrical insulation as used herein for describing certain coated regions of conductive lumen or other surfaces of the surgical instrument according to the invention refers to such surfaces being coated with an electrical insulator such that there is essentially no, or an acceptably low level of, electrical conduction between the coated region of the surface and another surface or medium through the electrically insulating layer at any electrical potentials up to the maximum electrical potential rating of the surgical instrument (about 1500 volts for typical electrocautery instruments as described herein). In other embodiments, the electrode(s) may comprise probes or conductive elements that are separate or separable from the fluid conducting lumen of the instruments.

An illustrative embodiment for a rotatably deployed surgical liquid jet instrument is shown in FIGs. 14A-14F. Referring to FIG. 14A, surgical instrument 600 includes a body 602 having a grasping region 604 configured to be held within the hand of an operator and an actuating element 606 that comprises a slidable sleeve or collar, which is used to deploy the distal end 608 of surgical instrument 600. Slidable sleeve 606 is positioned to be easily actuated by a single hand of an operator of instrument 600. Slidable sleeve 606 can enable the operator to hold body 602 in at least two different hand/grasping region 604 orientations, so that the operator can actuate slidable sleeve 606 while holding body 602 in either of the at least two hand/grasping region 604 orientations. For example, an operator can grip body 602 in a hand position where the thumb of the operator is located near the distal end of gripping region 604. In such position, the operator can actuate slidable sleeve 606 by moving the slidable sleeve with her thumb. In a second hand/grasping region orientation, the operator lumen or the evacuation lumen). For example, in one such alternative embodiment, the pressure lumen can be configured as described above (i.e. having an essentially continuous layer of an electrical insulator disposed along essentially its entire length, except in a region at its distal end surrounding the nozzle, which is uncoated and has a conductive surface providing a positive electrode) except also including a ground electrode disposed along or wrapped around the outer, insulated surface of the pressure lumen, where the ground electrode has a distal end that is disposed proximal to the conductive region of the outer surface of the lumen that provides the positive electrode. In such an alternative embodiment, the other lumen, which does not provide an electrode (e.g. the evacuation lumen in the above-described configuration), can be, if desired, constructed from an electrically non-conductive material, such as plastic.

FIG. 14A shows the distal end of instrument 600 submersed in an electrically conductive fluid in a surgical field 626. Pressure lumen 620 is coated with insulating layer 626 except at its distal tip. The uncoated, uninsulated distal tip 622 forms the positive integrated electrocautery electrode. Evacuation lumen 618, in the illustrated embodiment, is uninsulated except at distal tip 630. In the illustrated embodiment, distal tip 630 of evacuation lumen 618 is insulated in order to increase the minimum length of the conductive path 632 that electrocautery current travels along within surgical field 626 to prevent burning of tissue at the surface of the ground electrode 624 and to reduce any arcing, shorting, or burning of tissue that may be caused by providing a conductive path length that is too short. This can be especially important when performing electrocautery with surgical instrument 600 in an undeployed configuration, as shown, where the distal ends of pressure lumen 620 and evacuation lumen 618 are in very close proximity.

Upon operation of electrocautery, current will flow from electrode 622 and through the target tissue and electrically conductive fluid in surgical field 626 to a conducting surface at ground potential, for example the uninsulated surface 624 of evacuation lumen 618 and sheath 612, which is in electrical communication with lumen 618. Positive electrode 622 and ground electrode surface 624 of evacuation lumen 618 within the surgical field are preferably sized, based on the power rating of the power supply supplying power to the positive electrode, to focus electrical energy at the positive electrode and disperse the energy at the ground electrode. In typical prior art electrocautery instruments for performing bipolar electrocautery, the positive and ground electrodes are of essentially equal size. In such prior art instruments, essentially all of the tissue located between the electrodes gets desiccated by the lumen, as described below in the context of FIG. 14D. In an alternative embodiment, the inventive electrocautery instruments can also be operated in a bipolar mode by connecting the instrument to the monopolar output of a commercially available monopolar power supply for use in electrocautery. In such embodiments, pressure lumen 620, providing the positive electrode can be connected in electrical communication with the positive monopolar terminal of the power supply, while evacuation lumen 618, providing an electrode at ground potential, can be connected in electrical communication with the power supply's grounding connection. Also power supplied to the instrument from, for example, power supply 636 for performing electrocautery may, in some embodiments, be user controllable via a switch or other means provided on power supply 636, body 602, or via a remote switch, for example a foot operated switch, etc., as apparent to those of ordinary skill in the art.

In the illustrated embodiment, the pressure and evacuation lumen are constructed from a conductive material, such as stainless steel, that has a relatively low resistance to electrical current flow. The insulating coating provided on the outer surfaces of the lumen as described can comprise any insulating coating known to those of ordinary skill in the art. In one preferred embodiment, the coating comprises a polymeric coating formed on the surfaces of the lumen as shown using commercially available shrink-wrap tubing, for example polyvinylidene fluoride (PVDF) shrink wrap tubing. In another embodiment, the insulating coating comprises a polymeric coating (e.g. PVDF) formed on the outer surface by a variety of well known coating methods, for example spray coating, brush coating. dip coating, etc. with a variety of commercially available polymer layer forming solutions as known in the art. In one preferred embodiment, the insulating layer formed on pressure lumen 620 comprises a polymeric coating formed on the surface of the lumen using PVDF shrink-wrap tubing, while the insulating layer formed on the distal end of evacuation lumen 620 is formed by spray coating with a PVDF layer forming solution.

The thickness of the electrical insulating layer should be chosen to prevent electrical conduction through the layer during operation at maximum expected operating potentials of the instrument. The thickness will depend upon the well known electrical properties of the particular type of commercially available electrical insulation chosen and can be readily determined by those of ordinary skill in the art. In one embodiment, PVDF shrink-wrap tubing having a thickness of between about 0.004 inch and about 0.006 inch is used as the electrical coating for an instrument having a 1,500 volt peak-to-peak rating.

is between about 45 and 115 degrees, more typically between about 80 and about 100 degrees, and most typically about 90 degrees.

FIG. 14D shows a partially cutaway view of surgical instrument 600 showing more clearly the proximal end of body 602 and the connection of pressure lumen 620 to high pressure liquid supply conduit 662 and evacuation lumen 618 to evacuation conduit 664. Pressure lumen 620 can be connected to high pressure liquid supply conduit 662 via any of a wide variety of high pressure tubing connectors 667 well known in the art. Pressure lumen 620 and/or high pressure liquid conduit 662 are fixably mounted within body 602 to prevent movement of pressure lumen 620 with respect to body 602 during deployment. Evacuation lumen 618 rotates within body 602 upon movement of actuating element 606. Evacuation lumen 618 is connected to evacuation conduit 664, which is flexible and/or twistable within body 602, to allow evacuation lumen 618 to rotate.

FIG 14D also illustrates one embodiment for providing electrical connections between pressure lumen 620 and positive jack 640 and between evacuation lumen 618 and ground jack 644 within body 602. Positive jack 640 is electrically connected to pressure lumen 620 via a wire or other electrical connector 668, and ground jack 644 is electrically connected to evacuation lumen 618 via a wire or other electrical connector 669. Wire/connector 668 is, in turn, crimped to, soldered to, or otherwise connected in electrical contact (by any suitable means known to those of ordinary skill in the art) to an electrically conductive surface of pressure lumen 620 at point 670; likewise, wire/connector 669 is, in turn, crimped to, soldered to, or otherwise connected in electrical contact to an electrically conductive surface of pressure lumen 618 at point 672. Either or both of high pressure conduit 662 and high pressure connector 667 should be constructed from, or coated with, an electrically insulating material (e.g. a plastic material) to prevent exposure of an operator to electrical shock via contact with the region 674 of the high pressure conduit extending outside of body 602.

The actuating mechanism by which actuating element 606 causes rotation of rotatably mounted collar 610 and sheath 612, in order to deploy distal end 608 of instrument 600, is shown more clearly in FIGs. 14E and 14F. Referring to FIG. 14E, a cut away view of actuating element 606 is shown. Actuating element 606 can be generally cylindrical in shape and includes two apertures 676 and 678. Aperture 676 is located on the proximal surface of actuating element 606 and allows actuating element 606 to accommodate body 602 of instrument 600. Aperture 678 is located on the distal surface of actuating element 606 and has a circumference that is nearly equal or slightly greater than the outer circumference of jet nozzle region 704 may be bent with respect to axis 710 as shown in optional Step 4. In typical embodiments, nozzle region 704 is bent so that the axial center line 708 of jet nozzle region 704 forms an angle with respect to axis 710 that is between 45 degrees and 115 degrees, more typically between about 80 degrees and 100 degrees, and most typically about 90 degrees. Also preferably nozzle region 704 is bent with respect to tube 700 so that essentially no portion of jet nozzle region 704 projects radially beyond a perimeter that is defined by an outer surface of tube 700 outside of necked region 702. In addition to providing a method for forming liquid jet nozzles that have a relatively large length to minimum diameter ratio and that are relatively easy and inexpensive to manufacture, the inventive method also provides a pressure lumen having a maximum cross-sectional profile that does not exceed the diameter of the tubing comprising the pressure lumen. In addition, the nozzles formed by the method outlined in FIG. 15 also advantageously provide improved efficiency for forming a liquid jet as a high pressure liquid streams through the nozzle. The efficiency of forming the liquid jet is improved over nozzle designs comprising, for example, a hole bored in the side of a lumen, due to the fact that necked region 702 provides a smooth tapering flow path for the liquid flowing into nozzle region 704, thus reducing turbulence, recirculating flow patterns, and friction at the jet nozzle inlet. This effect is known in the fluid mechanical arts as the "vena contracta" effect and can improve fluid flow efficiencies through nozzles by as much as 30%.

FIGs. 16A and 16B illustrate a surgical instrument 1000 including integrated bipolar electrocautery that is similar in configuration with surgical instrument 100 previously shown in FIG. 1 above. The integrated electrocautery configuration for instrument 1000 is similar to that described above for instrument 600 of FIGs. 14A-14F, except that for instrument 1000, which includes a grinding burr 122 located at the distal end 116 and including a liquid jet-driven rotatable rotor and rotatable shaft for rotating the grinding burr, it is preferable to utilize the liquid cutting jet evacuation lumen 120 as the lumen providing positive electrode 1002 at the distal end of the surgical instrument. It is preferred to utilize evacuation lumen 120 as the positive electrode in surgical instrument 1000 because evacuation lumen 120 is connected within body 104 of the instrument to evacuation conduit connecting block 176 which, in turn, is connected to evacuation conduits 178, which extend from the proximal end of the surgical instrument. Evacuation conduit connecting block 176 and conduits 178 are constructed of electrically non-conductive polymeric materials that do not conduct electricity from evacuation lumen 120 to any surface of the instrument in contact with the user during of the instrument are, in preferred embodiments, essentially the same as that previously described for instrument 600 shown in FIGs. 14A-14F.

FIG. 16B shows the distal end 116 of instrument 1000 submersed in an electrically conductive fluid in a surgical field 1032. Evacuation lumen 120 is coated with electrically insulating layer 1009 except at its distal tip. The uncoated, uninsulated distal tip 1002 forms the positive integrated electrocautery electrode. Pressure lumen 118, in the illustrated embodiment, is uninsulated except at distal tip 1030. In the illustrated embodiment, distal tip 1030 of pressure lumen 118 is insulated (shaded region), as previously described above for evacuation lumen 618 of surgical instrument 600, in order to reduce any arcing, shorting, or burning of tissue that may be caused by providing a conductive path length that is too short. Upon operation of the electrocautery electrode 1002 current flows from electrode 1002 and through the target tissue and electrically conductive fluid in surgical field 1032 to a conducting surface at ground potential that is in electrical communication with the ground terminal of the power supply, for example the uninsulated surface 1031 of pressure lumen 118, as well as other conducting surfaces within surgical field 1032 that are in electrical communication with the pressure lumen, such as grinding burr 122, burr tip support 136, sheath 132, etc. Instrument 1000 could, in alternative embodiments, be connected to a power supply providing monopolar output for performing electrocautery, as was previously described for instrument 600. Also, in other embodiments, because the distal ends of evacuation lumen 120 and pressure lumen 118 are maintained at an essentially constant separation distance during operation of the device, unlike deployable device 600 shown previously in FIGs. 14A-14F, insulated tip 1030 of pressure lumen 118 can be eliminated (i.e., the entirety of the external surface of pressure lumen 118 may be electrically conductive) without unduly affecting performance of electrocautery with the instrument.

The inventive surgical instruments described herein enable the performance of a number of inventive surgical methods. For example, by utilizing the surgical instruments provided according to the invention, which provide both a liquid cutting jet and a rotatable component at the distal end of the instrument, surgical procedures may be performed involving both liquid jet cutting/ablating and other tasks that utilize or require rotation of a rotatable component in a surgical field, without the need for exchanging surgical instruments within the surgical field or providing multiple instruments to the surgical field. For example, the invention enables an operator of such an instrument to insert the surgical instrument into a surgical field of a patient, create a liquid cutting jet with the surgical instrument to cut or operating a liquid cutting jet to create an evacuation via eductor pump action, an operator with visual access to the surgical field can be able to visualize a trail of blood (i.e., a blood stream flowing along a stream line from the site of a bleed to the inlet of the source of evacuation provided by the surgical instrument) and can stop the bleeding with the instrument before visualization of the entire surgical field is compromised (i.e., before the entire surgical field is rendered opaque due to the presence of blood therein). Upon visualizing the trail of blood during the operation of the instrument, the user can move the surgical instrument within the surgical field along the trail of blood towards the bleeding vessel, while continuously providing evacuation to the instrument. Upon reaching the site of bleeding, the operator can place an electrocautery electrode provided on the surgical instrument in proximity to the bleeding vessel and apply an electrical signal to the electrode to electrocauterize the bleeding vessel to stop the bleeding therefrom. Such a method is particularly useful for endoscopic surgical procedures, for example arthroscopy procedures in the joint capsule of a patient, where the surgical field is visually monitored with an endoscopic camera.

Those skilled in the art would readily appreciate that all parameters listed herein are meant to be examples and that actual parameters will depend upon the specific application for which the methods and apparatus of the present invention are used. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, the invention may be practiced otherwise than as specifically described.

What is claimed:

7. The device as in claim 6, further comprising:

a liquid-jet target locatable opposite the jet opening at a predetermined distance therefrom to receive the liquid cutting jet when the instrument is in operation.

8. The device as in claim 6, further comprising:

an evacuation lumen, including a jet-receiving opening locatable opposite the jet opening at a predetermined distance therefrom to receive the liquid cutting jet when the instrument is in operation.

9. The device as in claim 8, wherein the evacuation lumen is shaped and positionable to enable evacuation of essentially all of the liquid comprising the liquid cutting jet from the jet-receiving opening to a proximal end of the evacuation lumen without the need for an external source of suction coupled in fluid communication with the evacuation lumen.

10. The device as in claim 8, wherein the body of the surgical instrument includes a liquid flow directing valve therein having an inlet in fluid communication with a source of high pressure liquid, a first outlet in fluid communication with the pressure lumen having sufficient burst strength to conduct a high pressure liquid towards the distal end of the instrument, and a second outlet in fluid communication with a second pressure lumen configured to conduct a high pressure liquid towards the liquid jet-driven rotor.

11. The device as in claim 1, wherein the component constructed and arranged for contact with tissue in a surgical operating field comprises a grinding burr.

12. The device as in claim 11, wherein the burr comprises a fluted burr.

13. The device as in claim 11, wherein the burr comprises a diamond burr.

14. The device as in claim 11, further comprising:

a sheath having a proximal end and a distal end, the sheath surrounding at least a portion of the rotatable shaft.

the nozzle is positioned within the body of the instrument so that the liquid rotor-driving jet emanating therefrom impacts a surface of the liquid jet-driven rotatable rotor, thereby imparting rotational motion to the rotor, such that there is essentially no change in hydrostatic pressure of the liquid comprising the liquid rotor-driving jet while in contact with the rotor, when the instrument is in operation.

23. The device as in claim 1, wherein the rotatable shaft has a longitudinal axis defining an axis of rotation of the shaft and the rotatable rotor rotates about an axis of rotation that is essentially perpendicular to the axis of rotation of the rotatable shaft, when the instrument is in operation.

24. The device as in claim 1, wherein the rotatable shaft has a longitudinal axis defining an axis of rotation of the shaft and the rotatable rotor rotates about an axis of rotation at a first rotational speed and the rotatable shaft rotates about the longitudinal axis defining an axis of rotation of the shaft at a second rotational speed that is different from the first rotational speed, when the instrument is in operation.

25. The device as in claim 1, wherein the rotatable rotor comprises a saw-tooth rotor.

26. A device comprising:

a surgical instrument having a distal end adapted to perform a surgical procedure on a patient and a proximal end adapted to be controllable by an operator, the instrument including:

a pressure lumen having sufficient burst strength to conduct a high pressure liquid towards the distal end of the instrument, the pressure lumen including at least one nozzle providing a jet opening and being shaped to form a liquid cutting jet as a liquid at high pressure flows therethrough; and

a rotatable shaft;

a surgical component drivable by the shaft, constructed and arranged for contact with tissue in a surgical operating field.

27. The device as in claim 26, wherein the rotatable shaft extends from the proximal end of the instrument towards the distal end of the instrument.

37. The device as in claim 30, wherein the component constructed and arranged for contact with tissue in a surgical operating field comprises a grinding burr.

38. The device as in claim 37, further comprising:

a sheath having a proximal end and a distal end, the sheath surrounding at least a portion of the rotatable shaft.

39. The device as in claim 38, wherein at least a portion the pressure lumen including at least one nozzle providing a jet opening and being shaped to form a liquid cutting jet as a liquid at high pressure flows therethrough and the evacuation lumen including a jet-receiving opening locatable opposite the jet opening at a predetermined distance therefrom to receive a liquid cutting jet are surrounded by the sheath.

40. The device as in claim 38, wherein essentially the entirety of the pressure lumen including at least one nozzle providing a jet opening and being shaped to form a liquid cutting jet as a liquid at high pressure flows therethrough and the evacuation lumen including a jet-receiving opening locatable opposite the jet opening at a predetermined distance therefrom to receive a liquid cutting jet are positioned external to the sheath.

41. The device as in claim 38, wherein the proximal end of the sheath is in fluid communication with an external source of suction to enable evacuation of tissue fragments and debris from a region of the surgical operating field surrounding the burr.

42. The device as in claim 38, wherein the rotatable shaft is constructed and arranged to generate an evacuation force tending to drive liquid and debris from the distal end of the sheath towards the proximal end of the sheath.

43. The device as in claim 26, wherein the surgical operating field comprises a joint capsule of a patient.

44. The device as in claim 26, further comprising:

a body of the surgical instrument;

a rotatable rotor, drivingly coupled to the rotatable shaft, when the instrument is in operation, such that rotation of the rotatable rotor causes a corresponding rotation of the rotatable shaft;

a pressure lumen having a proximal end, and a distal end, the pressure lumen having sufficient burst strength to conduct a high pressure liquid, the distal end of the pressure lumen including a nozzle therein that is shaped to form a liquid jet as a liquid at high pressure flows therethrough, where

the nozzle is positioned so that at least a portion of the liquid jet emanating therefrom impacts a surface of the rotatable rotor, thereby imparting rotational motion to the rotor, such that there is essentially no change in hydrostatic pressure of the liquid comprising the liquid jet while in contact with the rotor, when the instrument is in operation.

49. The device as in claim 48, wherein the proximal end of the instrument includes a body.

50. The device as in claim 49, wherein the rotatable shaft extends from the body of the instrument towards the distal end of the instrument.

51. The device as in claim 50, wherein the rotatable rotor is positioned within the body of the instrument and is drivingly coupled to a proximal end of the rotatable shaft, when the instrument is in operation.

52. The device as in claim 49, wherein the distal end of the pressure lumen and the nozzle are positioned within the body of the instrument.

53. The device as in claim 48, wherein the nozzle is positioned so that essentially the entirety of the liquid jet emanating therefrom impacts a surface of the rotatable rotor.

54. The device as in claim 48, further comprising:

a second pressure lumen having sufficient burst strength to conduct a high pressure liquid towards the distal end of the instrument, the second pressure lumen including at least one nozzle providing a jet opening and being shaped to form a liquid cutting jet as a liquid at high pressure flows therethrough.

62. The device as in claim 48, wherein the liquid at high pressure is supplied to the nozzle at at least 1000 psig.

63. The device as in claim 62, wherein the liquid at high pressure is supplied to the nozzle at at least 5000 psig.

64. The device as in claim 63, wherein the liquid at high pressure is supplied to the nozzle at at least 8000 psig.

65. The device as in claim 64, wherein the liquid at high pressure is supplied to the nozzle at at least 15,000 psig.

66. The device as in claim 65, wherein the liquid at high pressure is supplied to the nozzle at at least 30,000 psig.

67. The device as in claim 48, wherein the nozzle has a region of minimum cross-sectional diameter having a predetermined length, the ratio of the predetermined length to the minimum cross-sectional diameter being not less than about four.

68. The device as in claim 67, wherein the ratio of the predetermined length to the minimum cross-sectional diameter is not less than about six.

69. The device as in claim 68, wherein the ratio of the predetermined length to the minimum cross-sectional diameter is not less than about ten.

70. The device as in claim 48, wherein the nozzle is positioned so that the liquid jet emanating therefrom traverses a gas-filled gap before impacting a surface of the rotatable rotor when the instrument is in operation.

71. The device as in claim 70, wherein essentially no portion of the rotatable rotor is submerged in a liquid when the instrument is in operation.

inserting a surgical instrument into a surgical field of a patient;

creating a liquid cutting jet with the surgical instrument;

cutting or ablating a first selected tissue of the patient with the liquid cutting jet;

rotating a rotatable component of the same surgical instrument;

contacting a rotating surface of the rotatable component with a second selected tissue of the patient; and

grinding, cutting, or abrading the second selected tissue with the rotating surface.

83. The method as in claim 82, further comprising after the creating step, the step of:

directing the liquid cutting jet towards a jet-receiving opening in an evacuation lumen of the surgical instrument.

84. The method as in claim 83, further comprising:

removing liquid comprising the liquid cutting jet and the first selected tissue from the surgical field without applying a source of external suction in fluid communication with the evacuation lumen.

85. The method as in claim 82, wherein the rotatable component comprises a grinding burr.

86. The method as in claim 85, wherein the second selected tissue comprises bone.

87. The method as in claim 82, further comprising, after the grinding step, the step of:

evacuating at least a portion of any debris and fragments of the second selected tissue generated during the grinding step from the surgical field.

88. The method as in claim 82, wherein the rotating step comprises:

supplying a rotatable shaft in the instrument, the shaft having a distal end, which includes the rotatable component, and a proximal end;

coupling the proximal end of the shaft in driving engagement with a rotatable rotor positioned within a body of the surgical instrument, such that when the instrument is in operation, rotation of the rotatable rotor causes a corresponding rotation of the rotatable shaft;

94. The pressure-tight sealing component as in claim 93, wherein seal is able to withstand a differential in pressure of at 50,000 psi. without leakage of fluid therethrough.

95. The pressure-tight sealing component as in claim 89, wherein the element comprises a main body portion having a cylindrical shape with a first outer diameter.

96. The pressure-tight sealing component as in claim 95, wherein the flared sealing flange portion has a predefined length and extends away from a surface of the main body portion of the element so as to form a cantilevered circumferential flange thereon.

97. The pressure-tight sealing component as in claim 96, wherein the element has a second outer diameter defined by an outermost periphery of the flange portion, which second outer diameter exceeds the first outer diameter.

98. The pressure-tight sealing component as in claim 97, wherein the second outer diameter exceeds the first outer diameter by at least about 1%.

99. The pressure-tight sealing component as in claim 98, wherein the second outer diameter exceeds the first outer diameter by at least about 3%.

100. The pressure-tight sealing component as in claim 98, wherein the second outer diameter exceeds the first outer diameter by at least about 5%.

101. The pressure-tight sealing component as in claim 100, wherein the second outer diameter exceeds the first outer diameter by at least about 10%.

102. The pressure-tight sealing component as in claim 96, wherein the flange portion of the element is pivotally flexible with respect to the main body portion.

103. The pressure-tight sealing component as in claim 97, wherein the cylinder containing the element has an internal diameter exceeding the first outer diameter but not exceeding the second outer diameter.

112. The pressure-tight sealing component as in claim 89, wherein the element forms a subcomponent of a liquid flow directing valve.

113. The pressure-tight sealing component as in claim 112, wherein the liquid flow directing valve includes a shaft therein having two plastic elements mounted thereon, the two plastic elements being separated one from the other by a spacer disposed therebetween.

114. The pressure-tight sealing component as in claim 112, wherein the liquid flow directing valve has an inlet connectable in fluid communication with a source of high pressure liquid, a first outlet, and a second outlet.

115. The pressure-tight sealing component as in claim 114, wherein the liquid flow directing valve forms a subcomponent of a surgical instrument and is contained within a housing of the instrument, the surgical instrument further including a liquid jet-powered rotatable rotor, a rotatable shaft, the rotatable rotor being constructed and arranged to drive the rotatable shaft in rotation, and a pressure lumen having sufficient burst strength to conduct a high pressure liquid towards a distal end of the instrument, the pressure lumen including at least one nozzle providing a jet opening and being shaped to form a liquid cutting jet as a liquid at high pressure flows therethrough.

116. The pressure-tight sealing component as in claim 115, wherein the first outlet of the liquid flow directing valve is connectable in fluid communication with the pressure lumen having sufficient burst strength to conduct a high pressure liquid towards the distal end of the instrument, and the second outlet of the liquid flow directing valve is connectable in fluid communication with a second pressure lumen configured to conduct a high pressure liquid towards the liquid jet-driven rotor.

117. The pressure-tight sealing component as in claim 116, wherein the liquid flow directing valve is configured to have three user-selectable positions, a first position directing a high pressure liquid from the inlet to the first outlet, a second position directing a high pressure liquid from the inlet to the second outlet, and a third position directing a high pressure liquid from the inlet to both the first outlet and the second outlet at the same time.

a liquid jet-driven rotatable rotor, drivingly coupled to the rotatable shaft, when the instrument is in operation, such that rotation of the liquid jet-driven rotatable rotor causes a corresponding rotation of the rotatable shaft, where

the rotatable rotor rotates about an axis of rotation at a first rotational speed and the rotatable shaft rotates about the longitudinal axis defining an axis of rotation of the shaft at a second rotational speed that is different from the first rotational speed, when the instrument is in operation.

124. The device as in claim 123, wherein the rotatable rotor comprises a saw-tooth rotor.

125. The device as in claim 123, wherein the rotatable rotor comprises a curved-vane rotor.

126. The device as in claim 123, wherein the rotatable rotor comprises a Terry rotor.

127. The device as in claim 123, wherein the rotatable rotor is drivingly coupled to the rotatable shaft by a gear reduction mechanism.

128. The device as in claim 127, wherein the first rotational speed exceeds the second rotational speed by at least a factor of about 2.

129. The device as in claim 128, wherein the first rotational speed exceeds the second rotational speed by at least a factor of about 5.

130. The device as in claim 129, wherein the first rotational speed exceeds the second rotational speed by at least a factor of about 10.

131. The device as in claim 130, wherein the first rotational speed exceeds the second rotational speed by at least a factor of about 20.

132. The device as in claim 131, wherein the first rotational speed exceeds the second rotational speed by at least a factor of about 30.

a surgical instrument having a distal end adapted to perform a surgical procedure on a patient and a proximal end adapted to be controllable by an operator, the instrument including:

a rotatable shaft;

a surgical component drivable by the shaft, constructed and arranged for contact with tissue in a surgical operating field;

a liquid jet-driven rotatable saw-tooth rotor, drivingly coupled to the rotatable shaft, when the instrument is in operation, such that rotation of the liquid jet-driven rotatable saw-tooth rotor causes a corresponding rotation of the rotatable shaft.

144. The device as in claim 143, wherein the rotatable saw-tooth rotor has a diameter between about 0.5 inch and about 10 inches.

145. The device as in claim 144, wherein the rotatable saw-tooth rotor has a diameter about 1 inch.

146. The device as in claim 143, wherein the rotatable saw-tooth rotor contains between about 10 and about 200 teeth.

147. The device as in claim 146, wherein the rotatable saw-tooth rotor contains about 80 teeth.

148. The device as in claim 143, wherein the rotatable saw-tooth rotor includes a plurality of liquid jet-impacting surfaces, each of which impacting surfaces is oriented essentially perpendicularly to at least one liquid jet impacting thereon at at least one rotational position of the rotatable rotor.

149. The device as in claim 148, wherein when the rotor is in a rotational position such that an impacting surface is oriented essentially perpendicularly to the liquid jet impacting thereon, essentially the entirety of the liquid jet impacts on the impacting surface of the rotor.

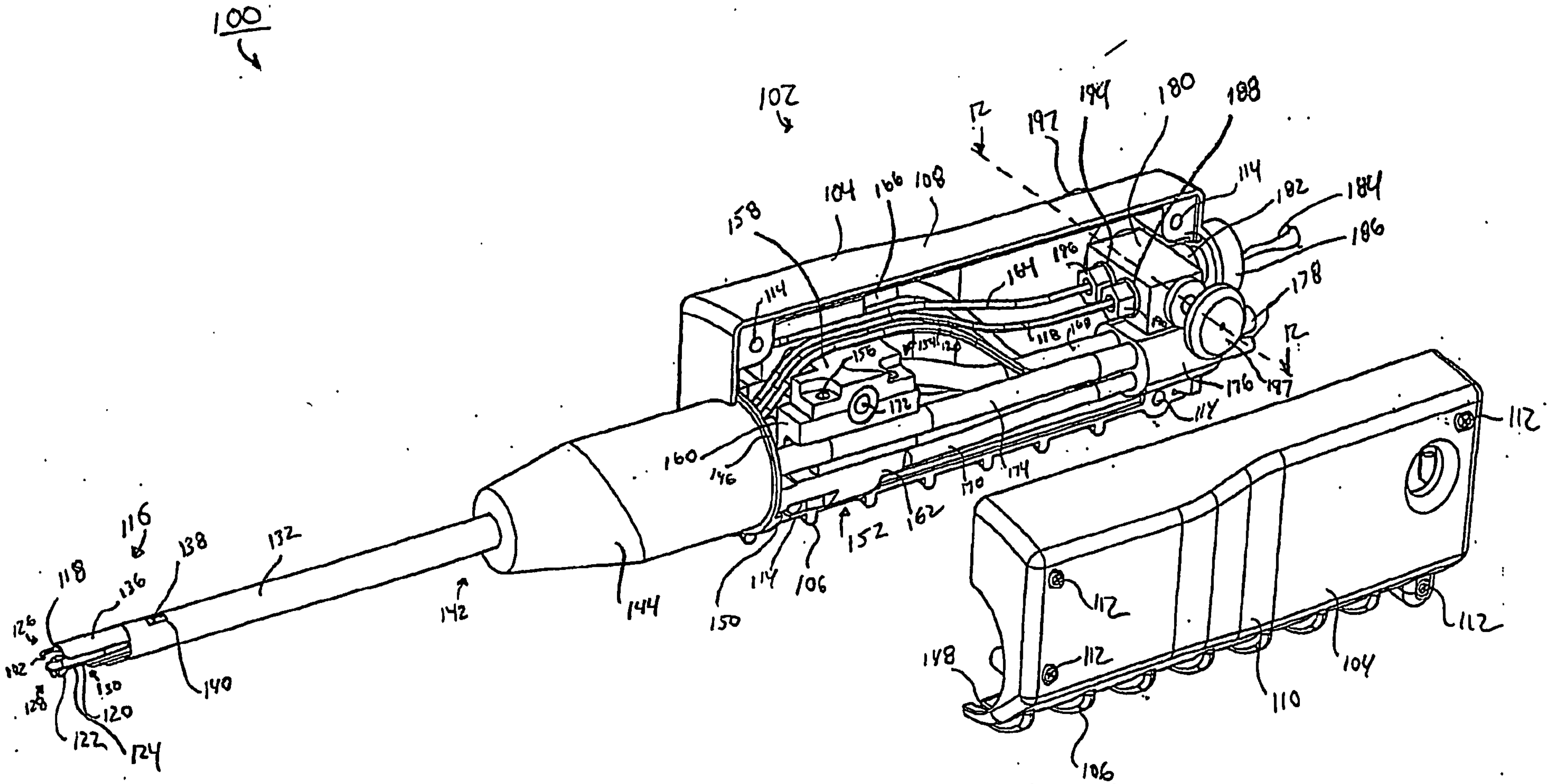

FIG 1

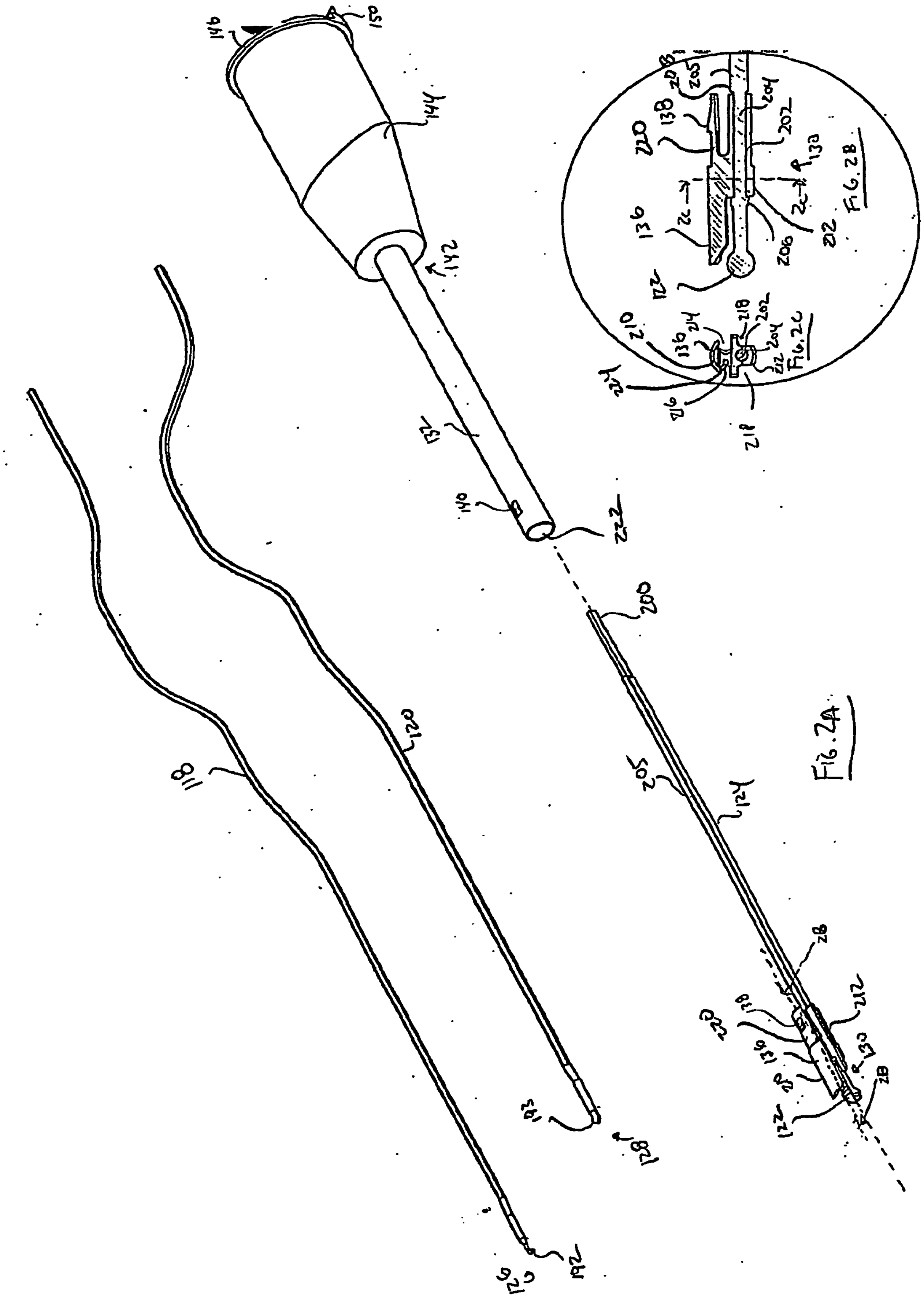

FIG. 2A

FIG. 2B

FIG. 2C

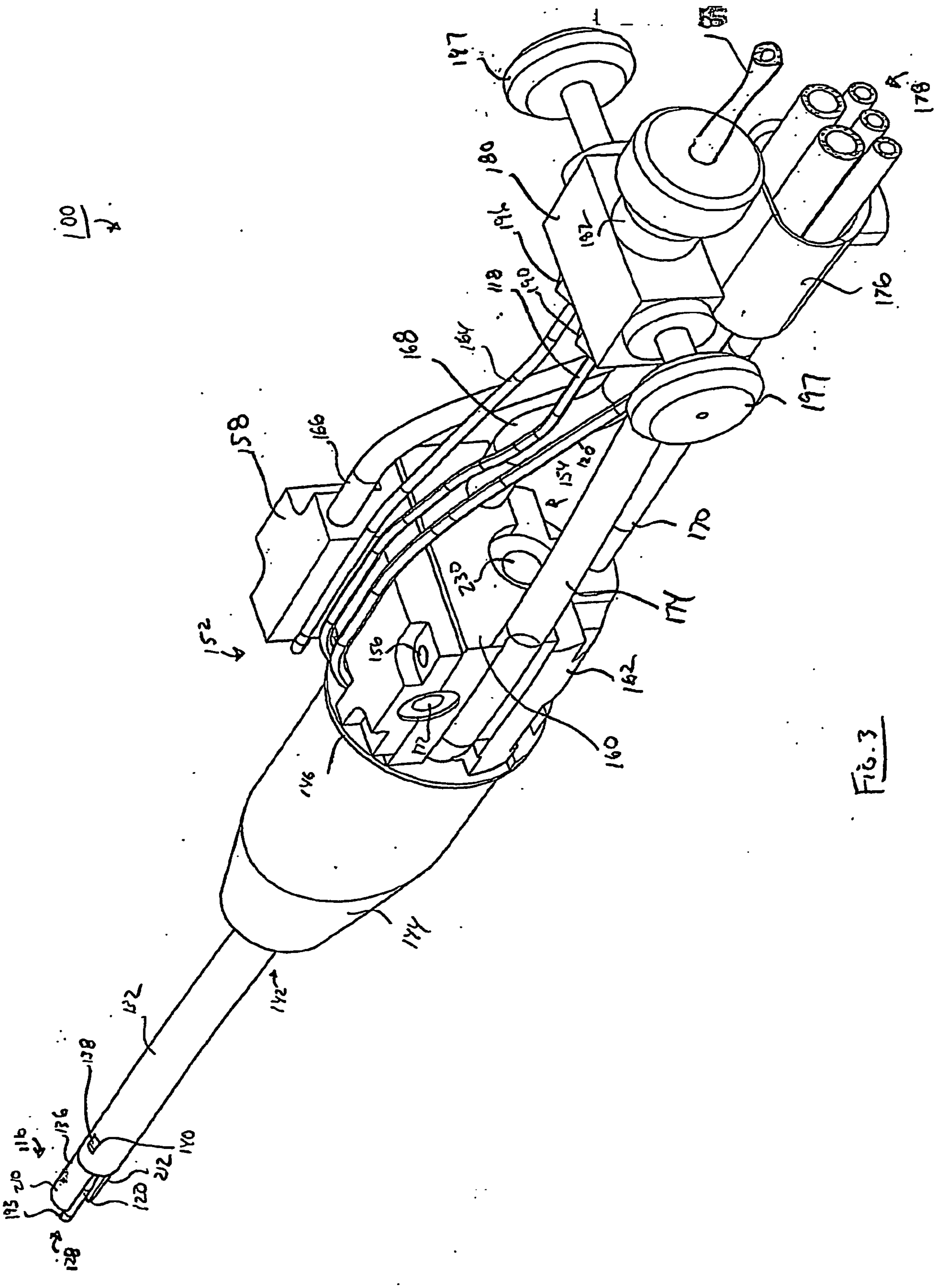
R

Fig. 3

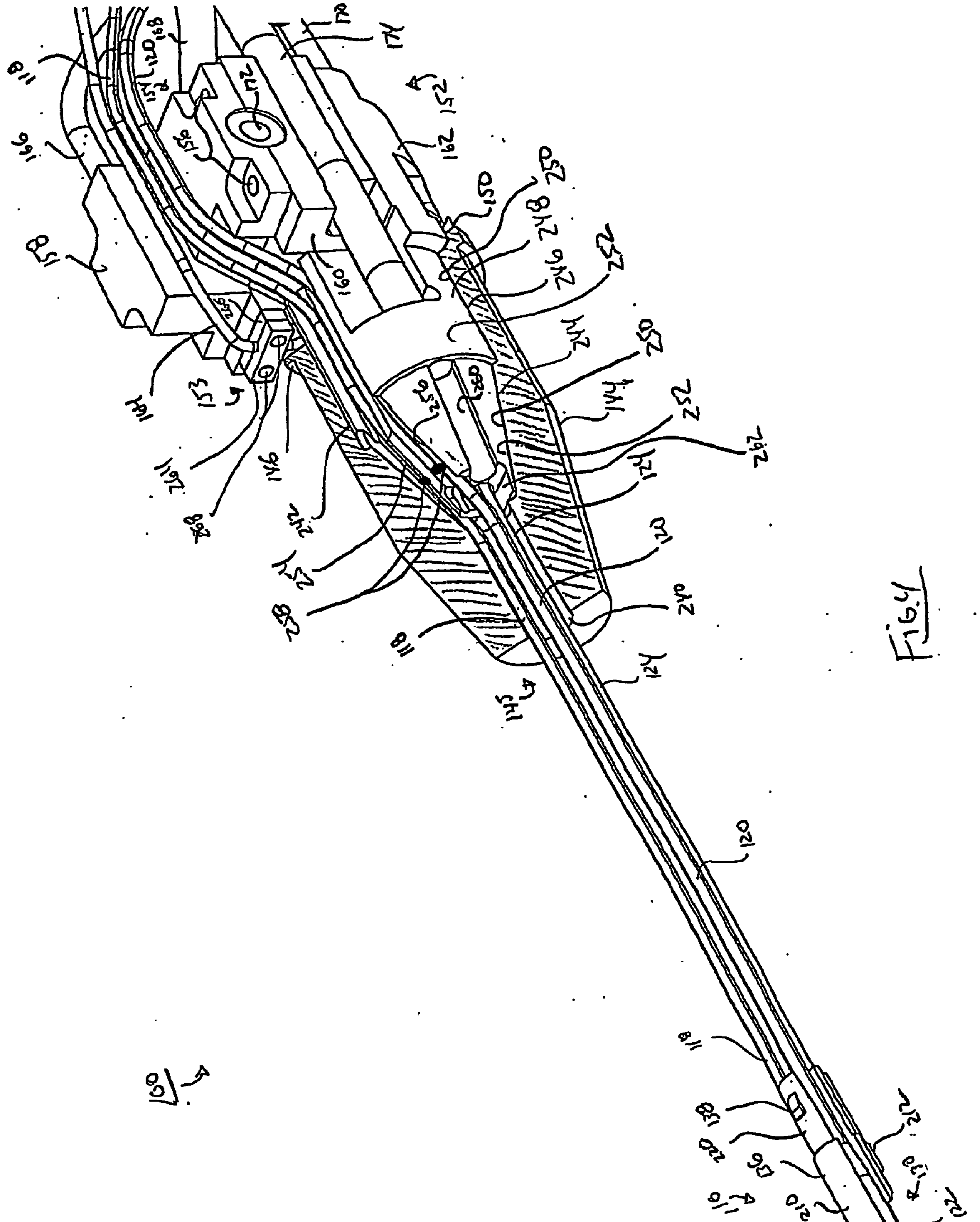

FIG. 4

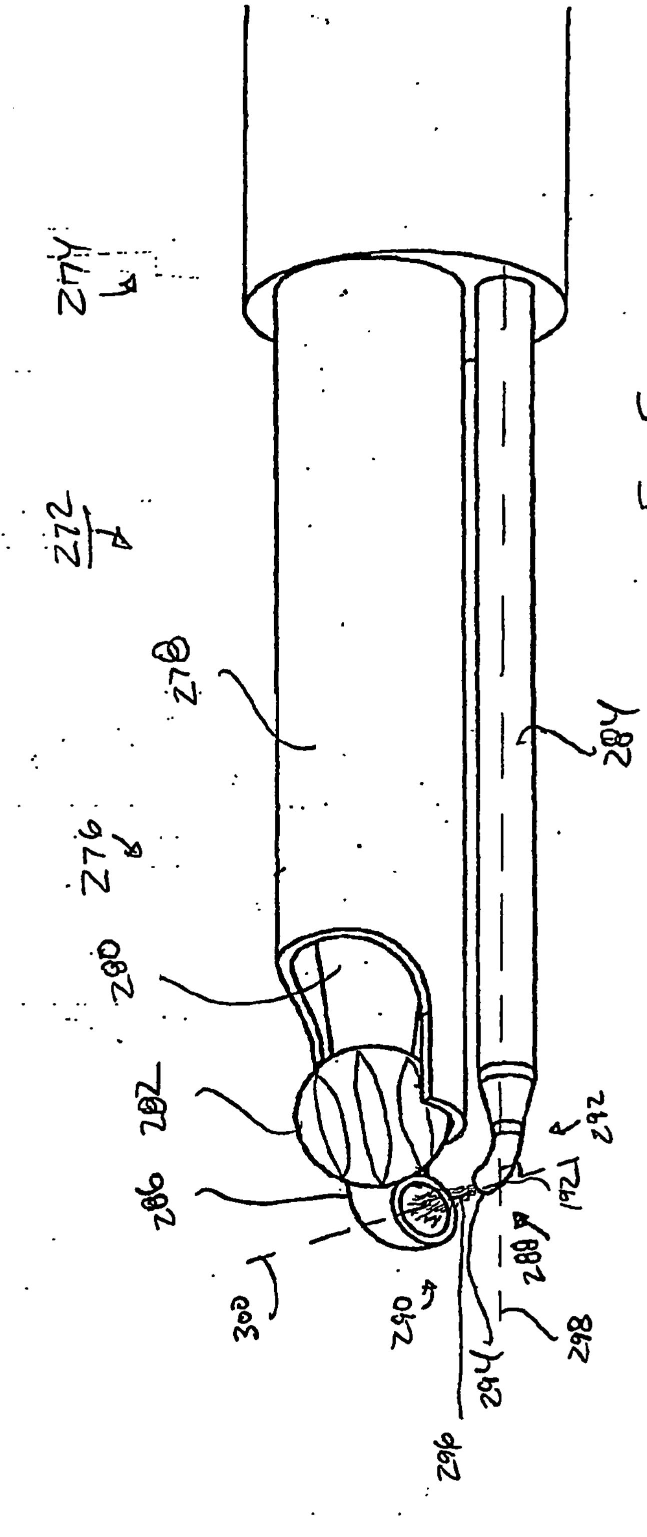

FIG. 5A

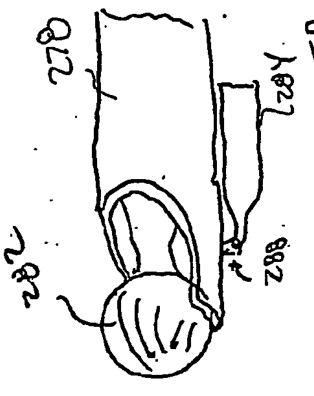

FIG 5B

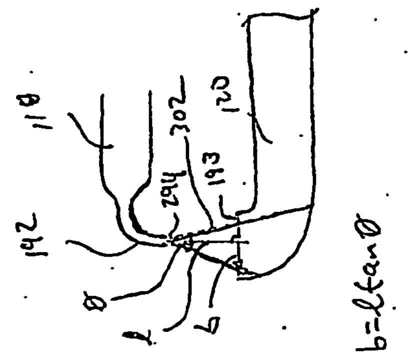

FIG 6C

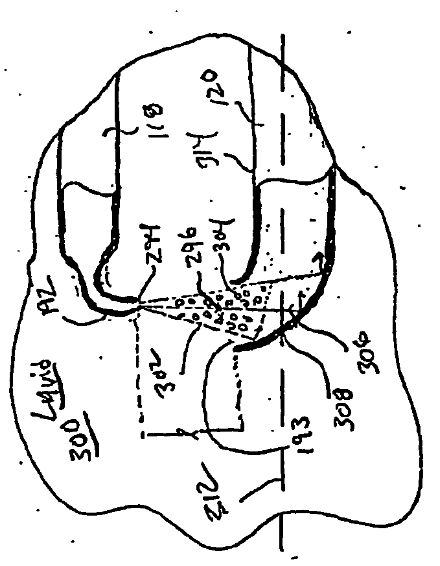

FIG 6A

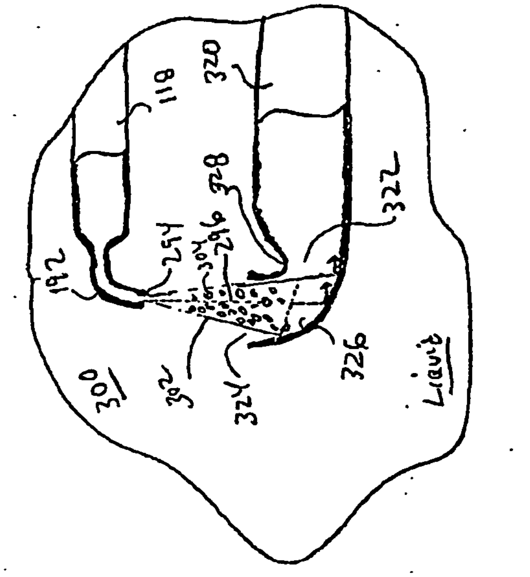

FIG 6B

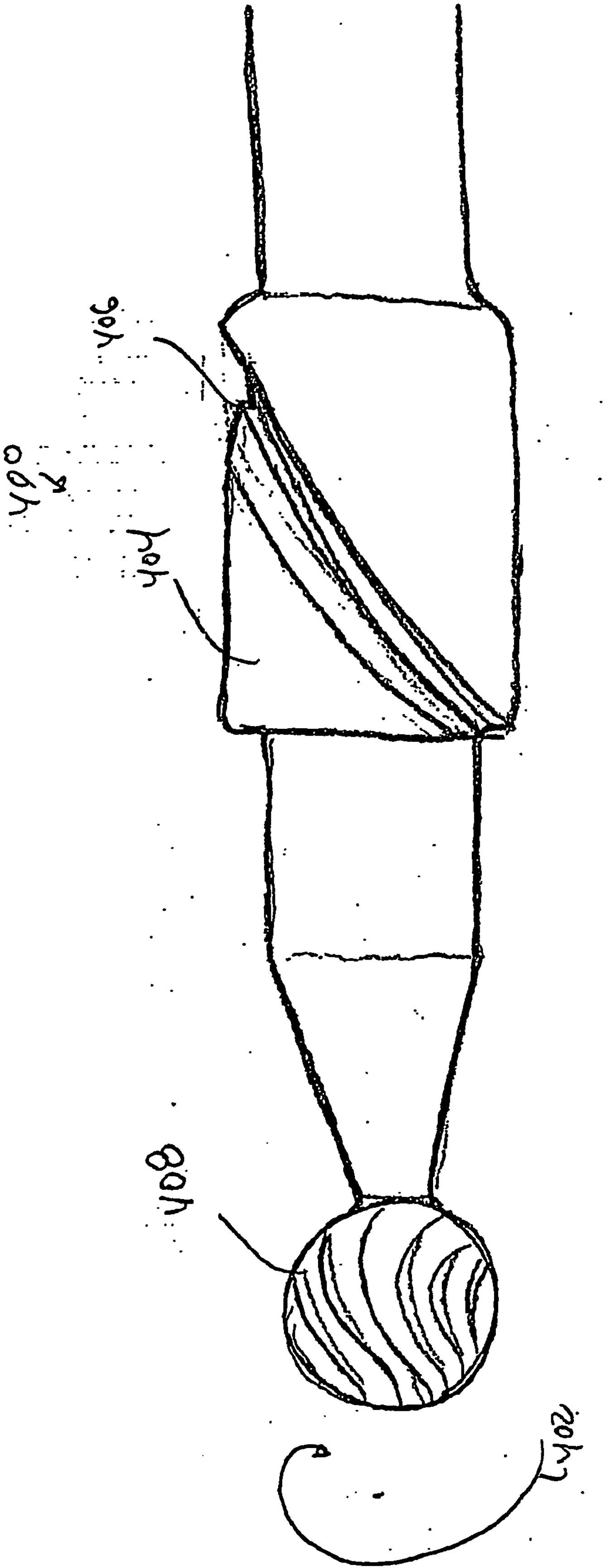

FIG. 7A

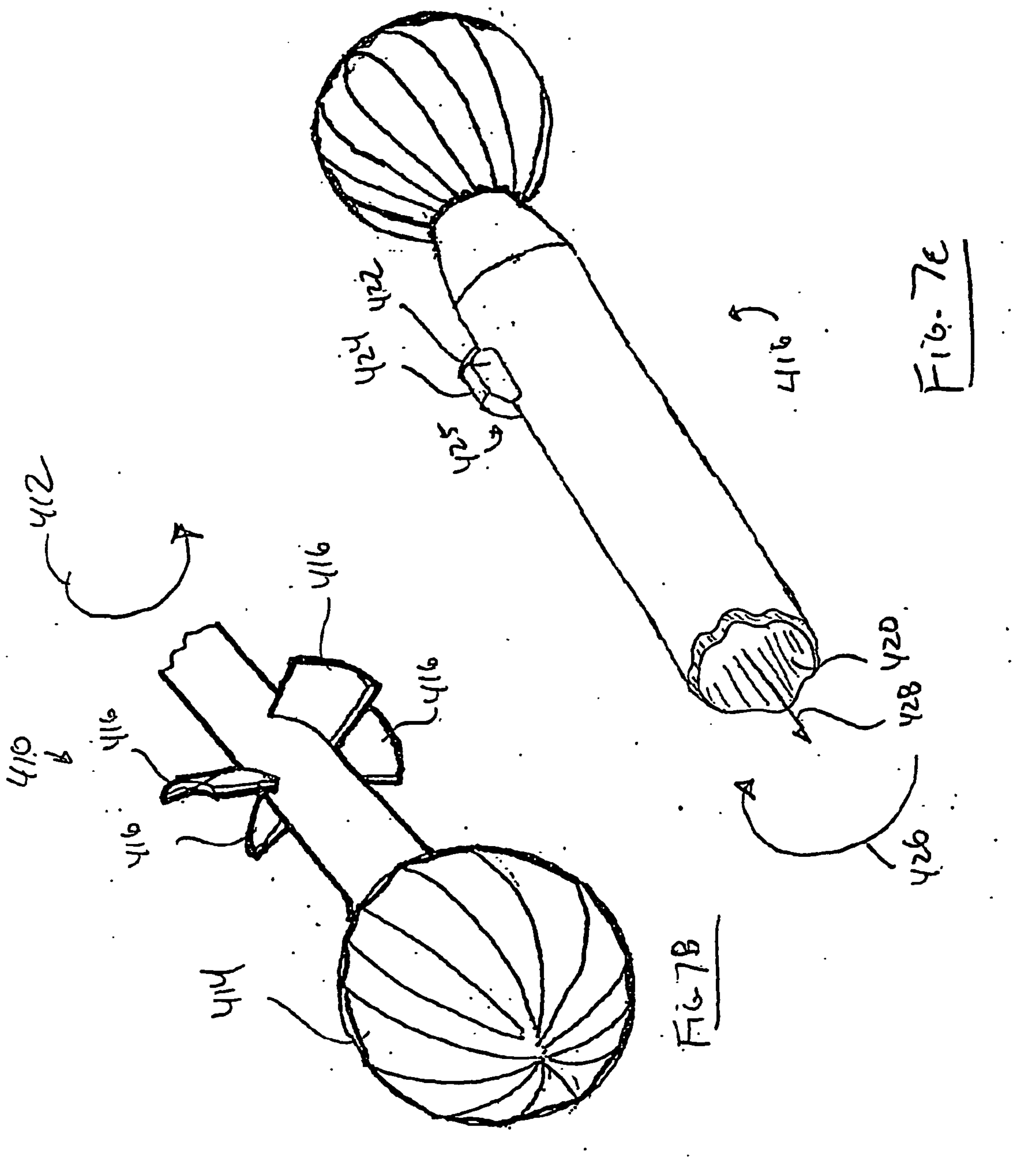

Fig 7B

Fig. 7E

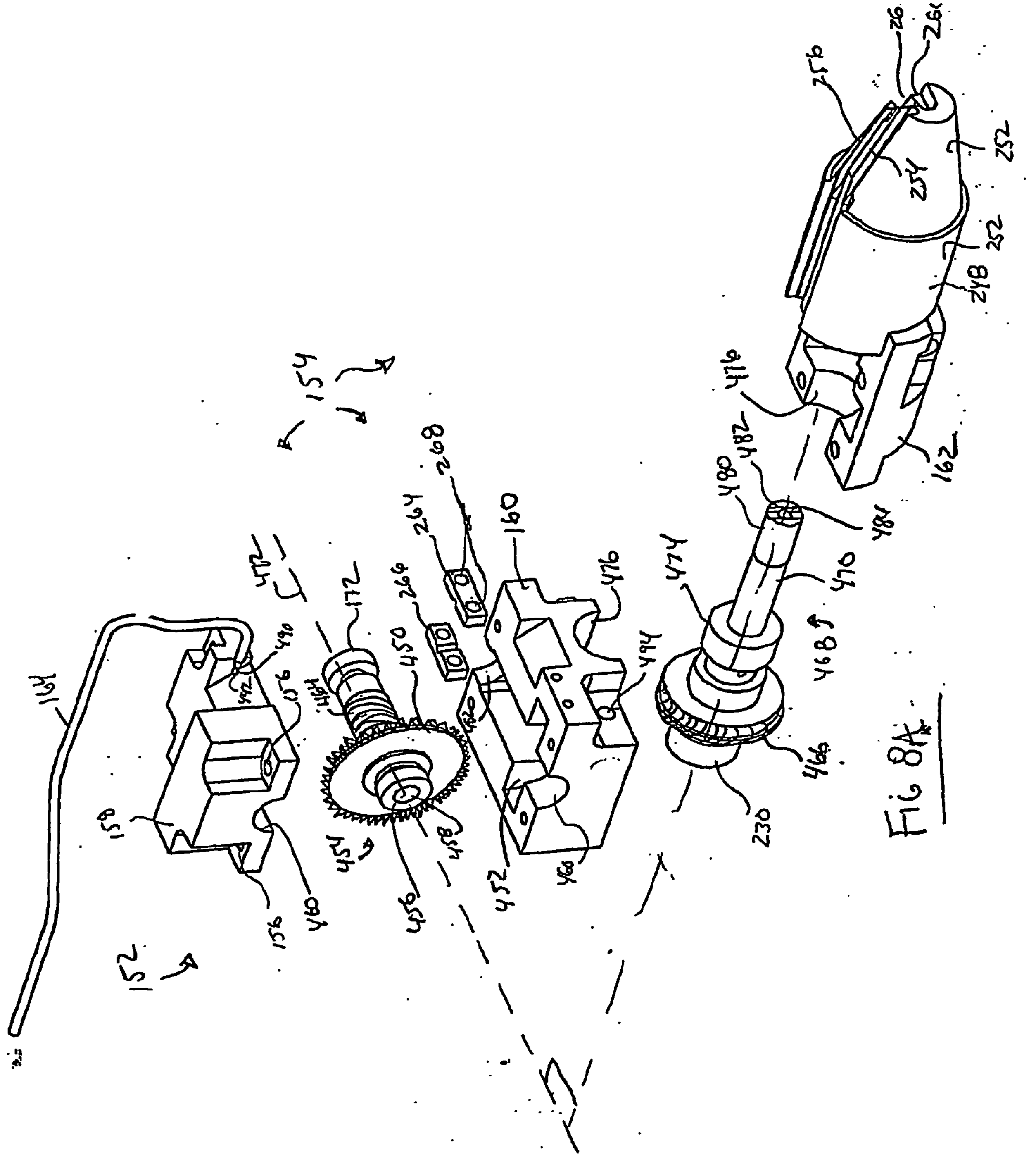

Fig 8A

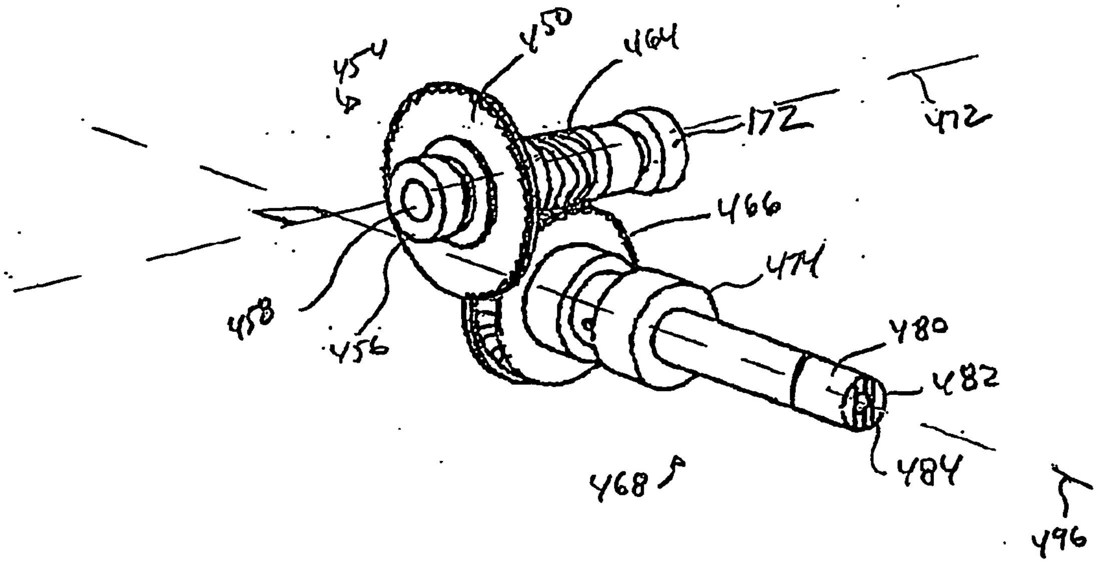

Fig 8B

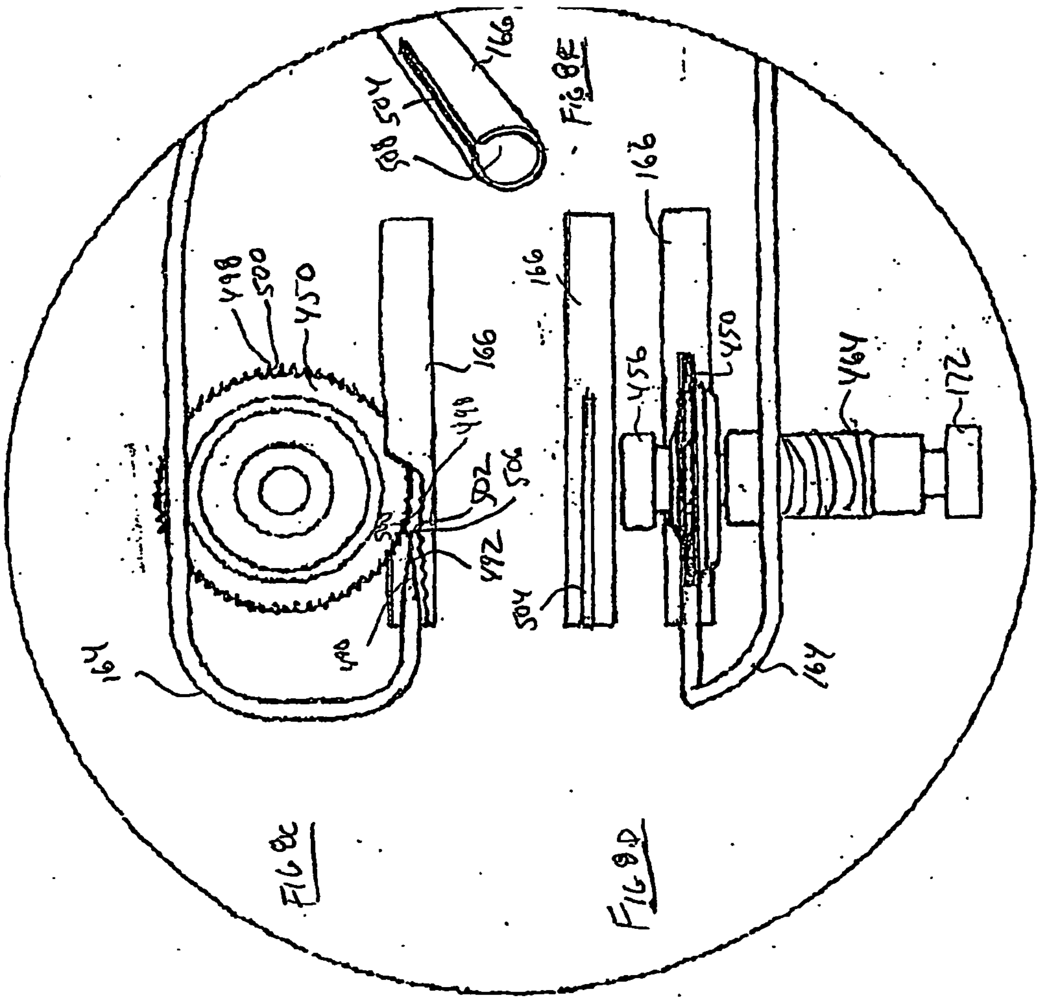

FIG 8E

FIG 8C

FIG 8D

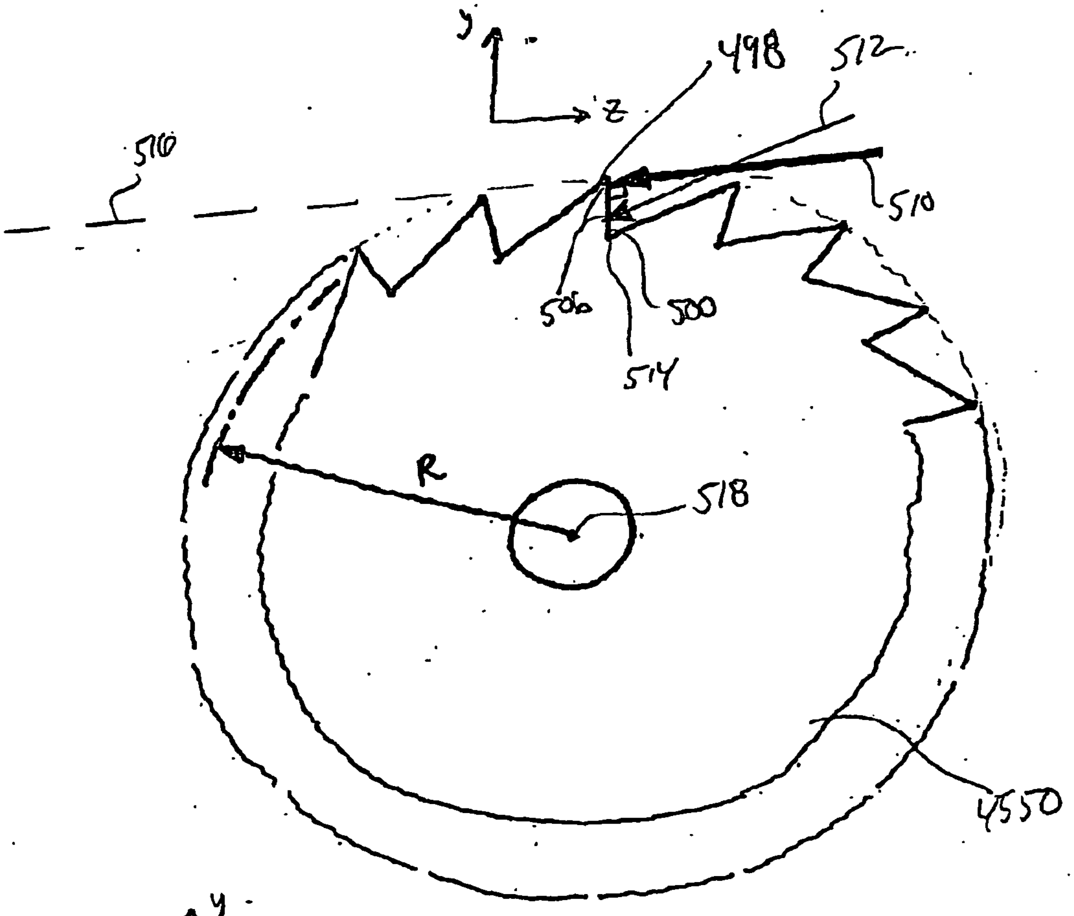
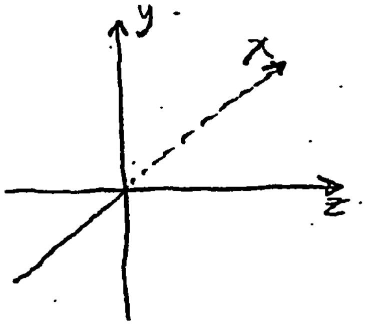
y
z
R
y
x
z

FIG 9A

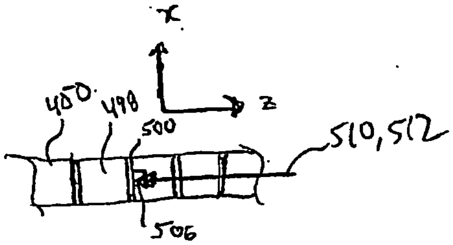
x
z
400
498
500
510, 512
506

FIG. 9B

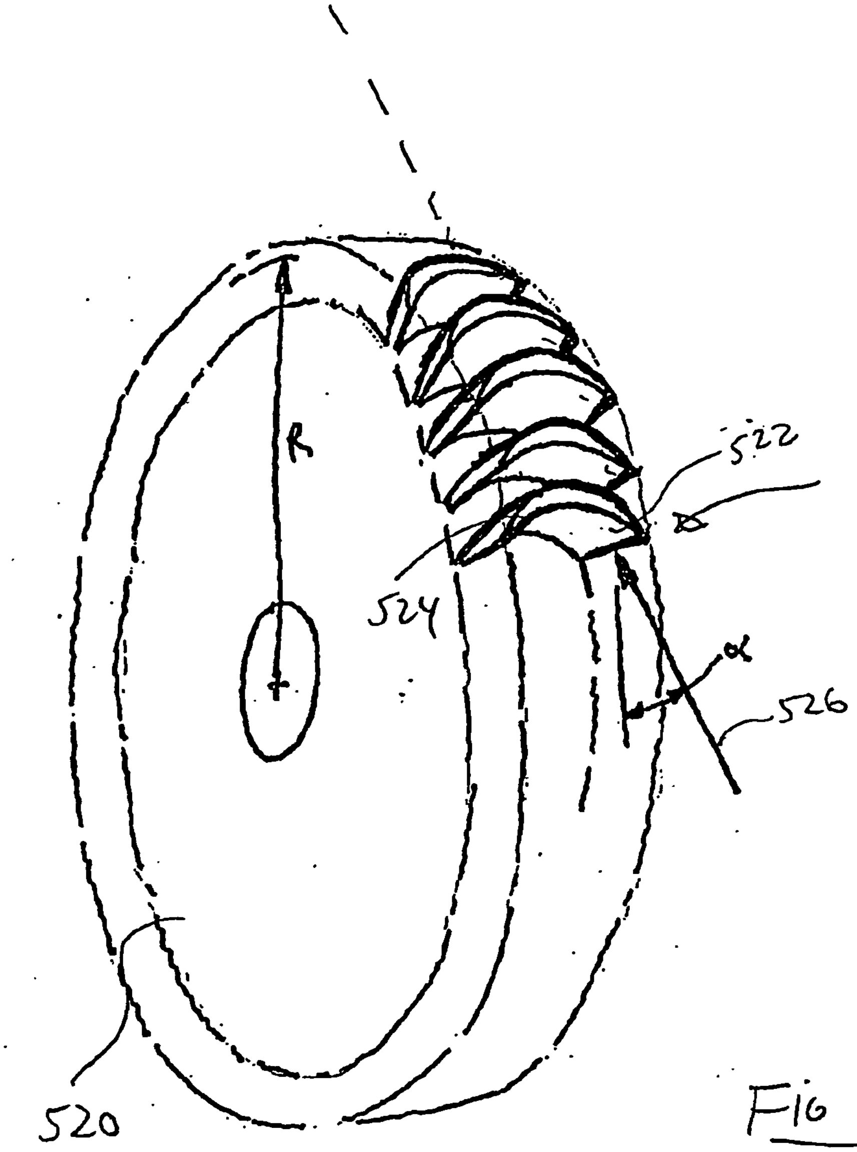

Fig 10A

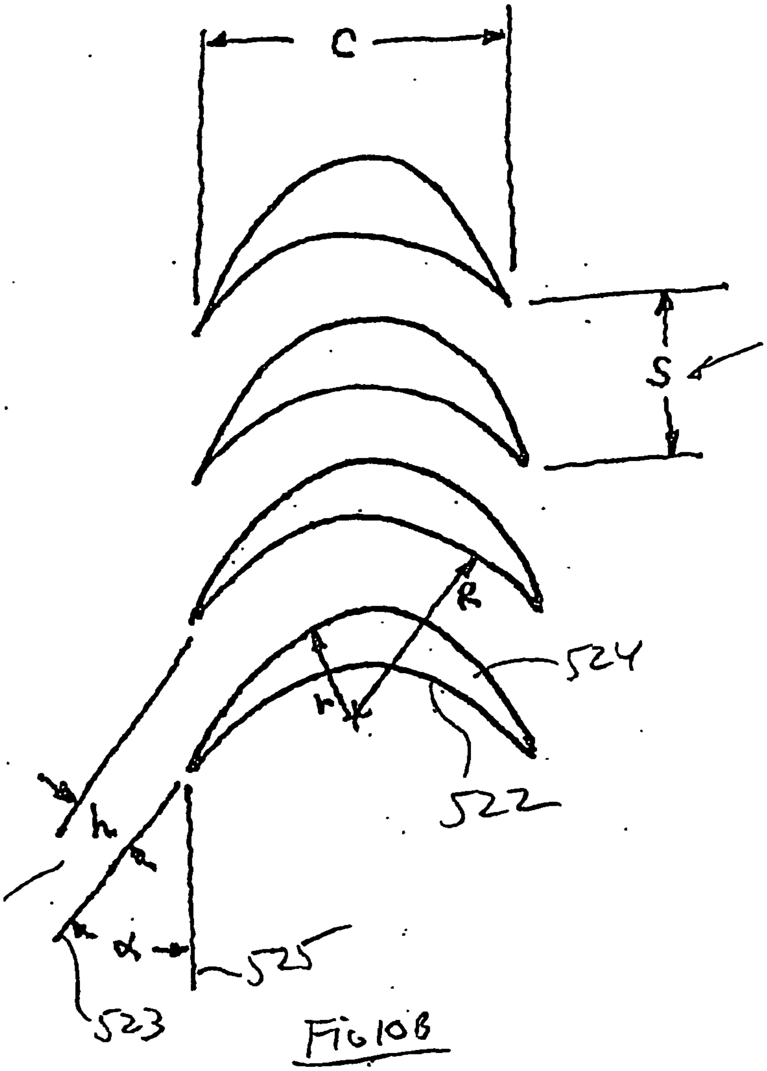

FIG 10B

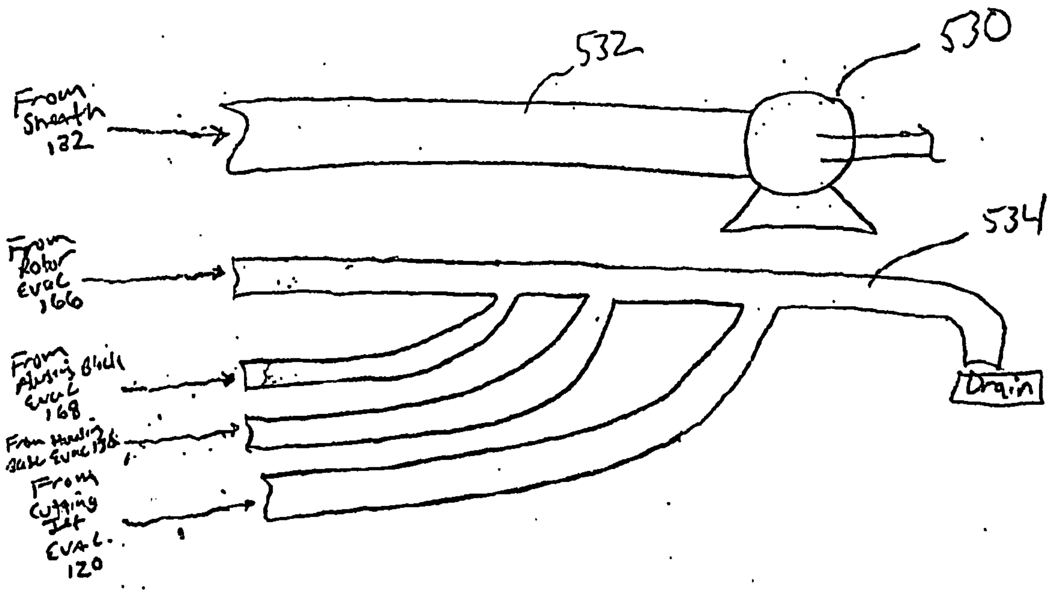
530
532
534
From Sheath 132
From Rotor Evac 166
From Housing Block Evac 168
From Housing Base Evac 138
From Cutting Jet Evac 120
Drain

FIG 11A

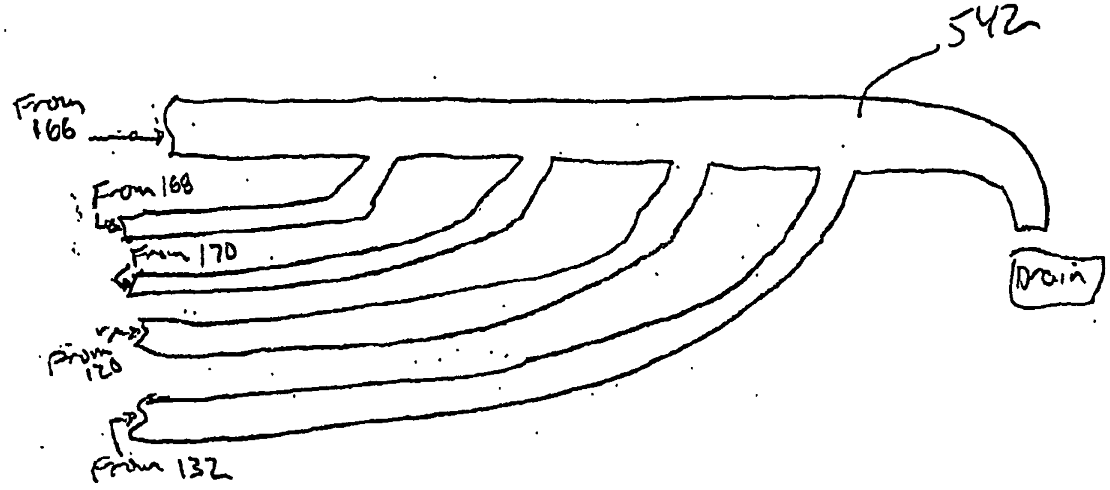

FIG 11B

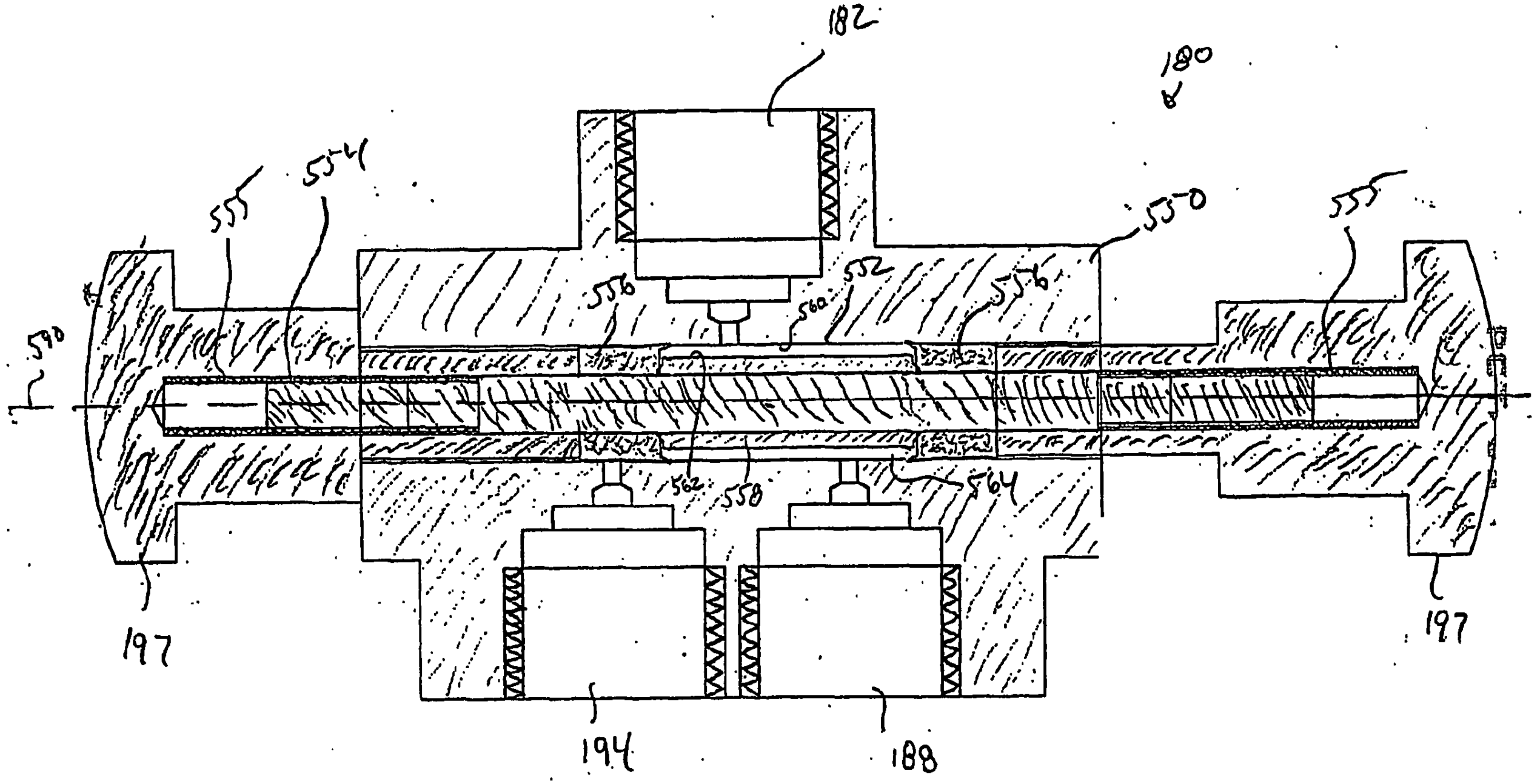

FIG 12

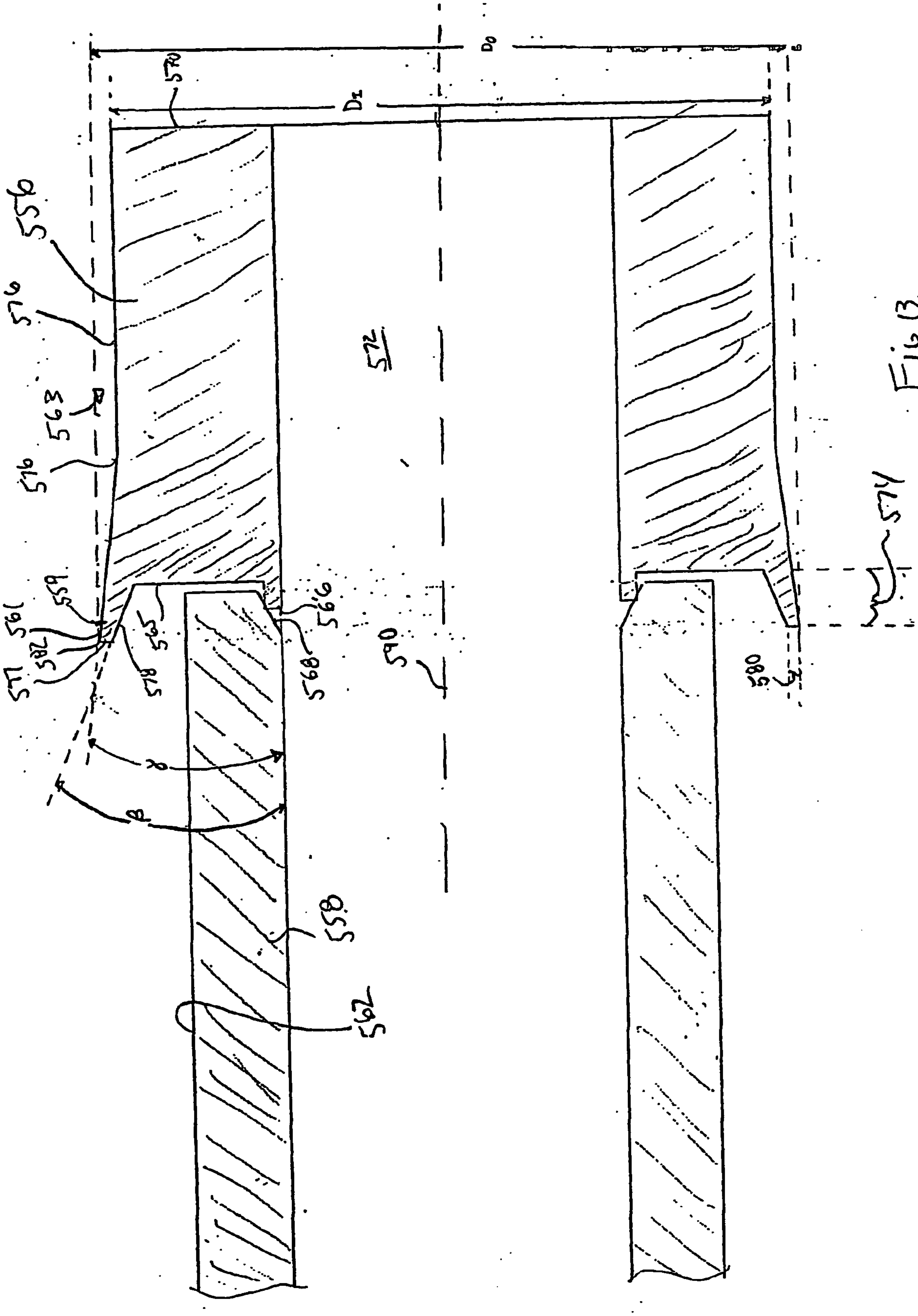
D0
DI
α
β

Fig 13

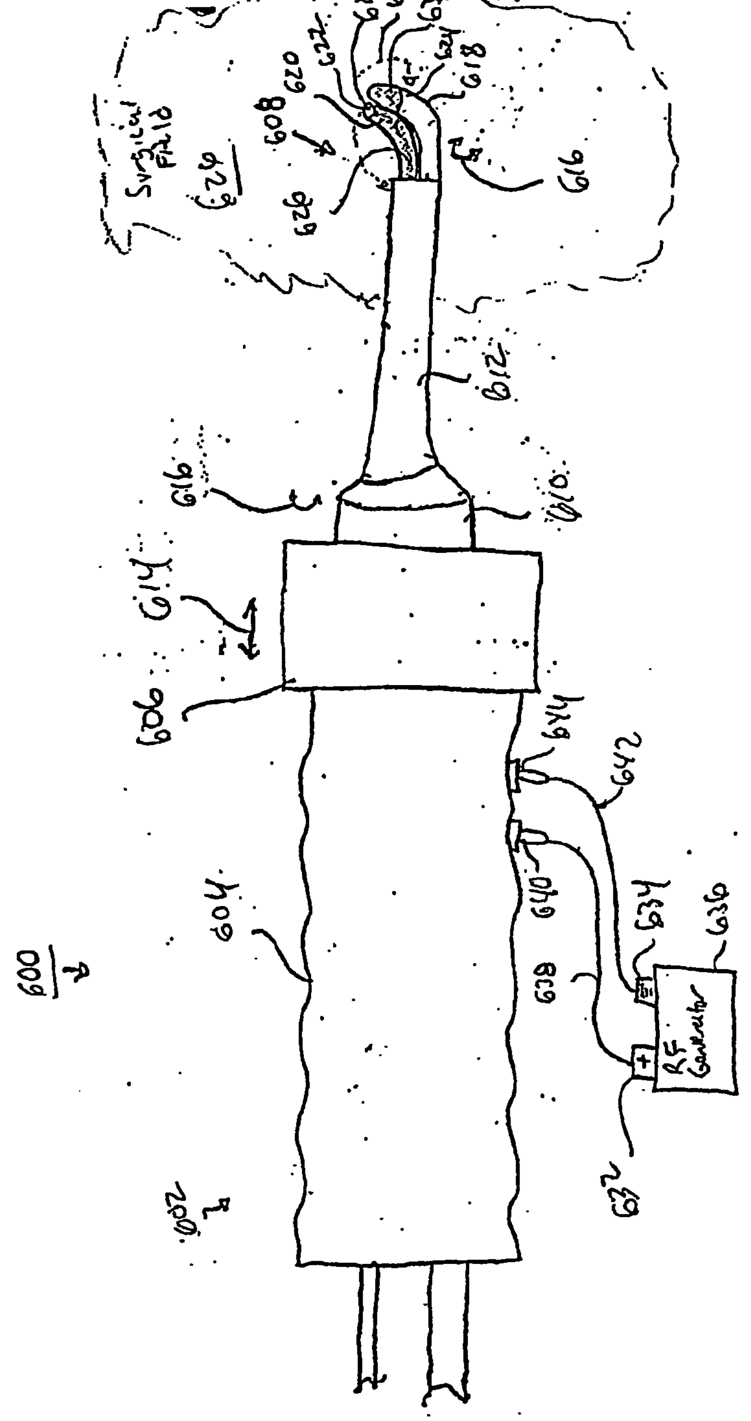
Surgical Field
RF Generator
+
-

Fig 14A

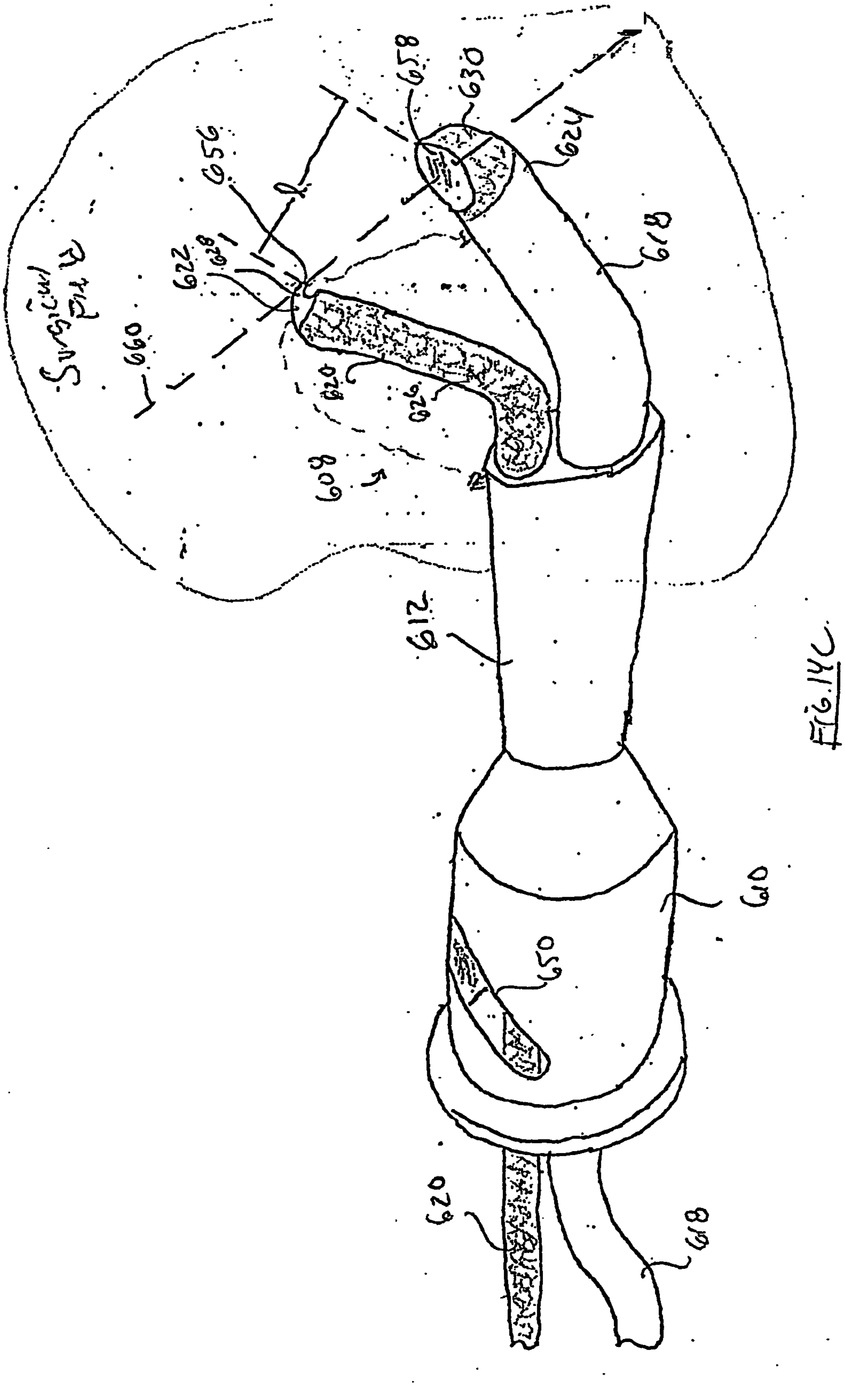
ℓ
Surgical Path

FIG. 14C

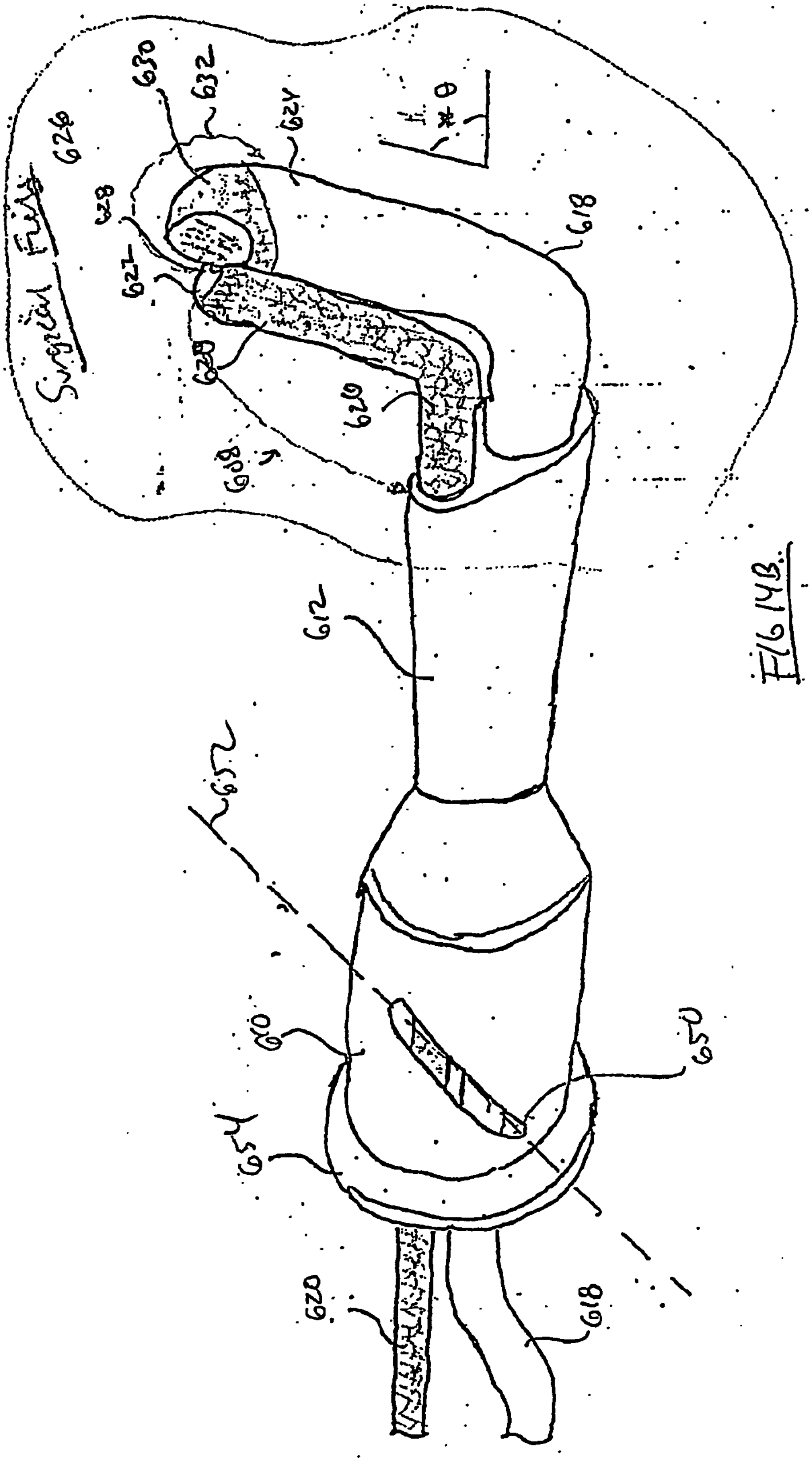
Surgical Field
θ

FIG 14B.

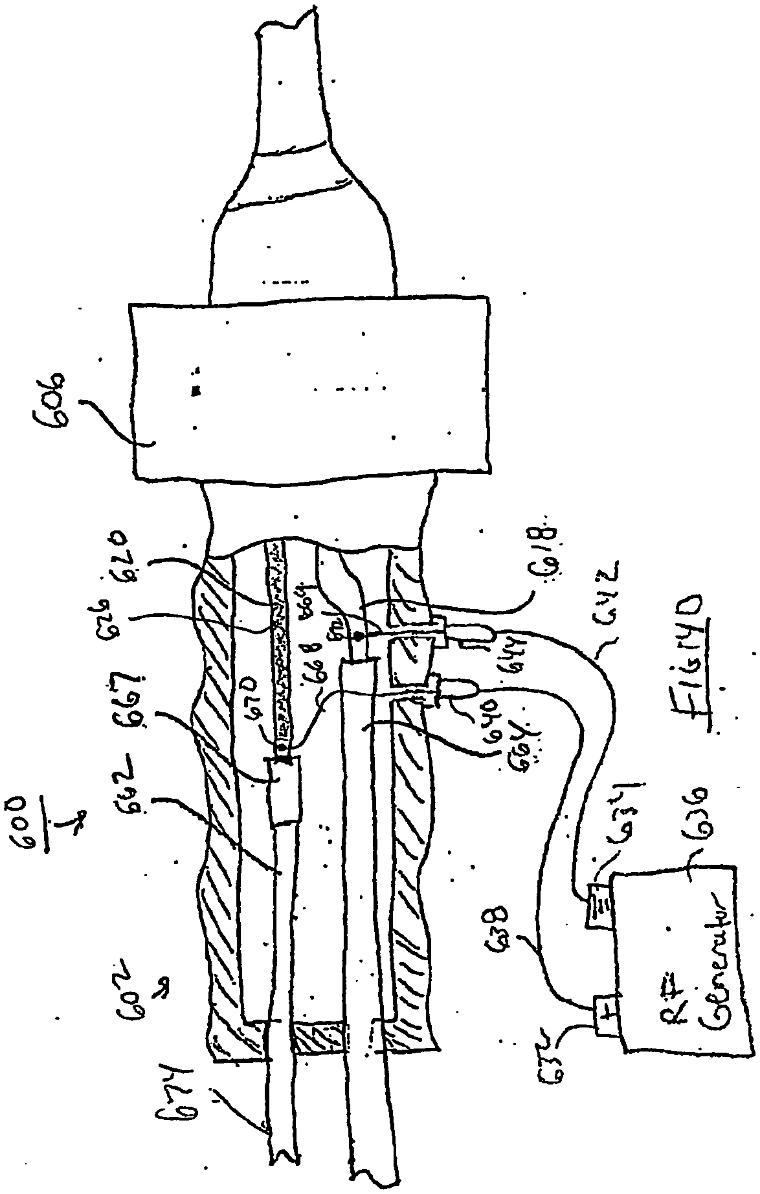
RF Generator
+
-

Fig14D

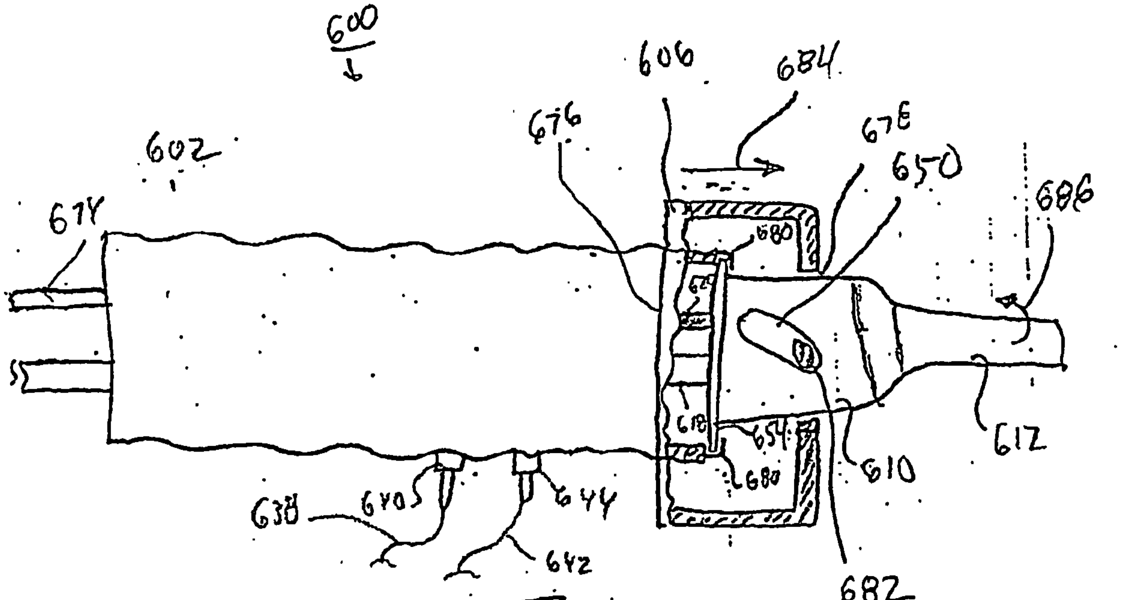

FIG 14E

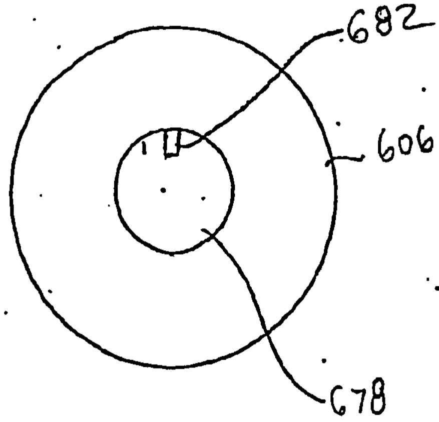

FIG 14F

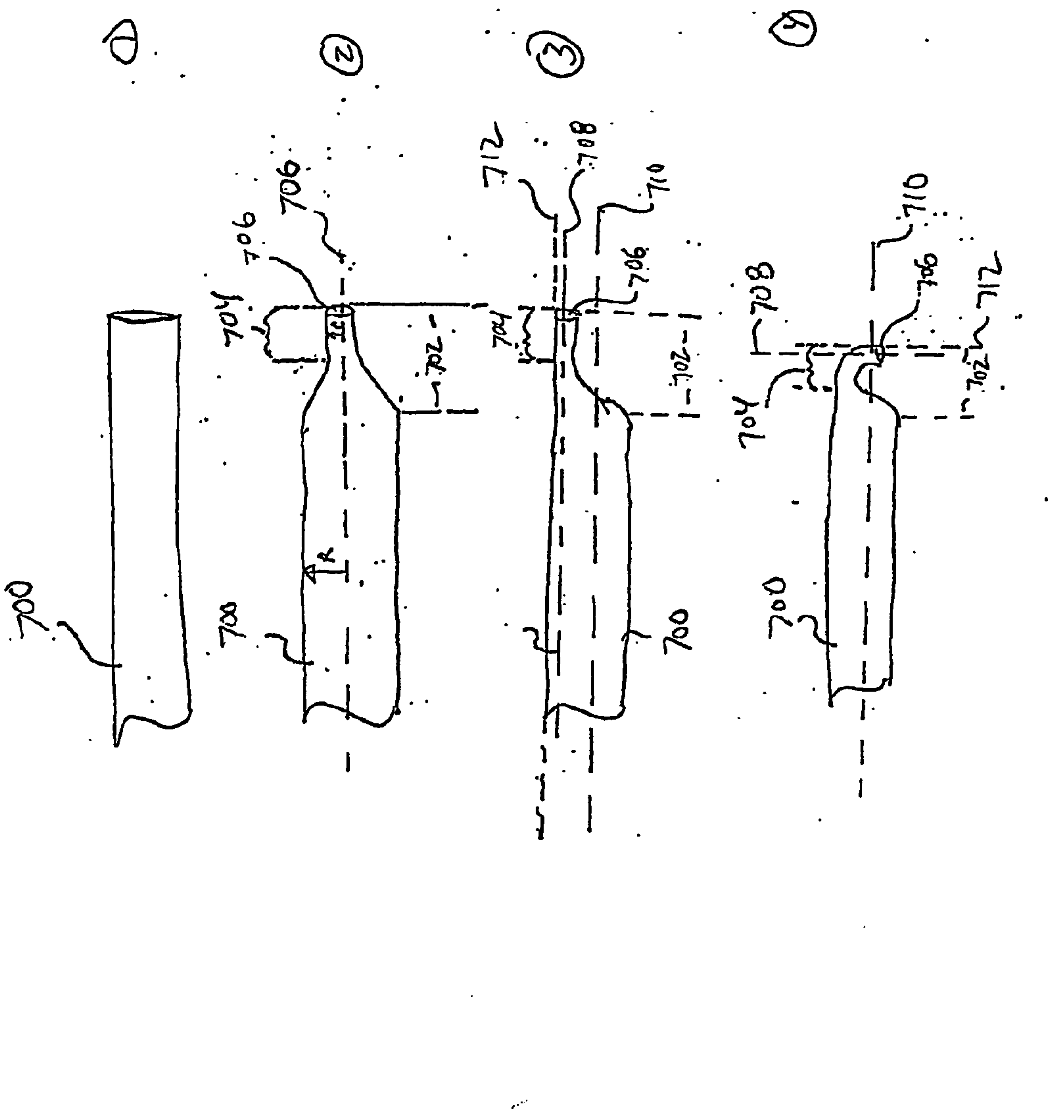
①
②
③
④
R

FIG 15

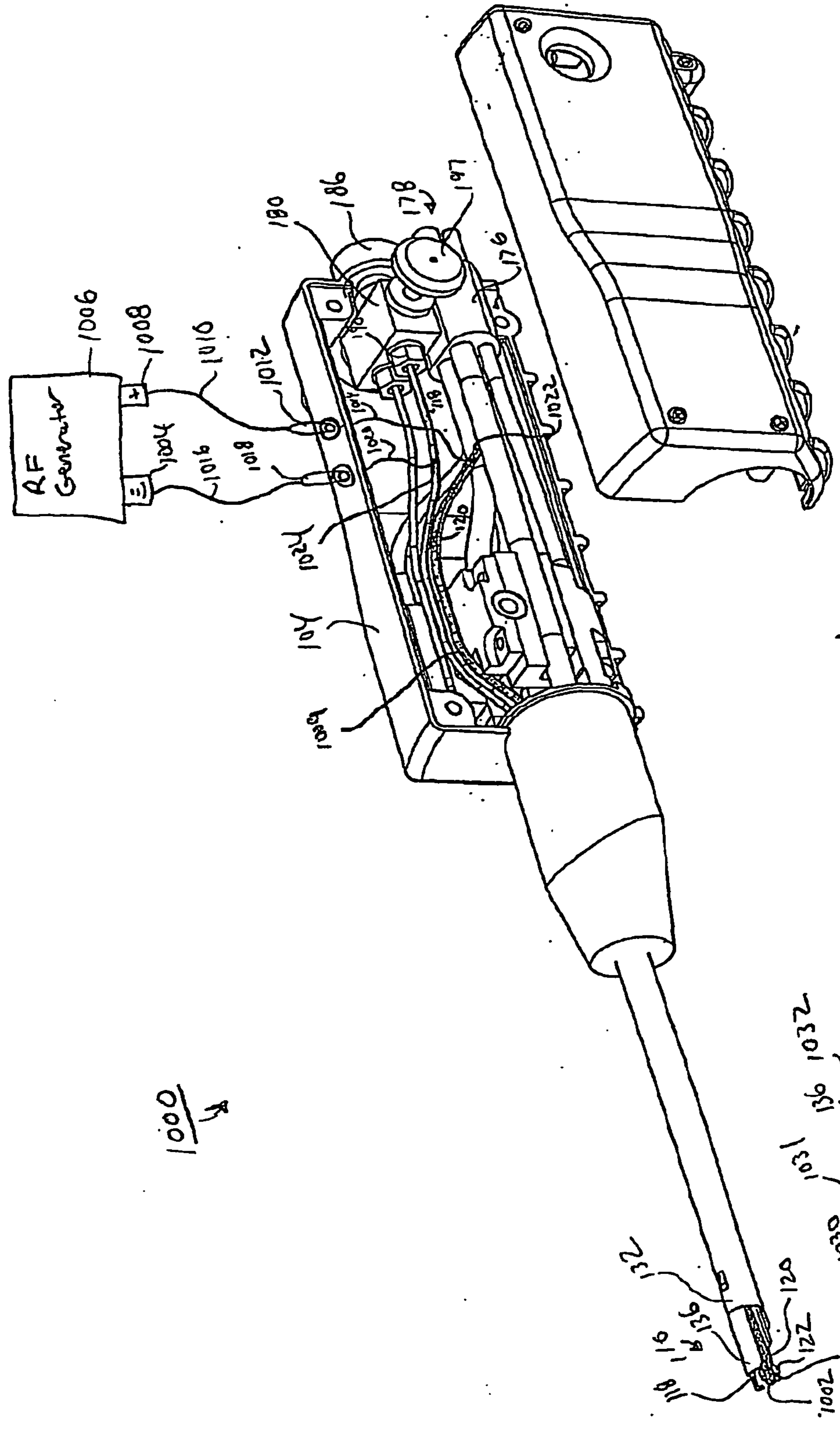

Fig 16A

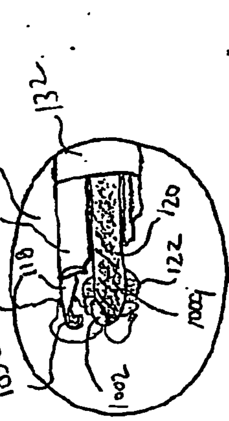

Fig 16B